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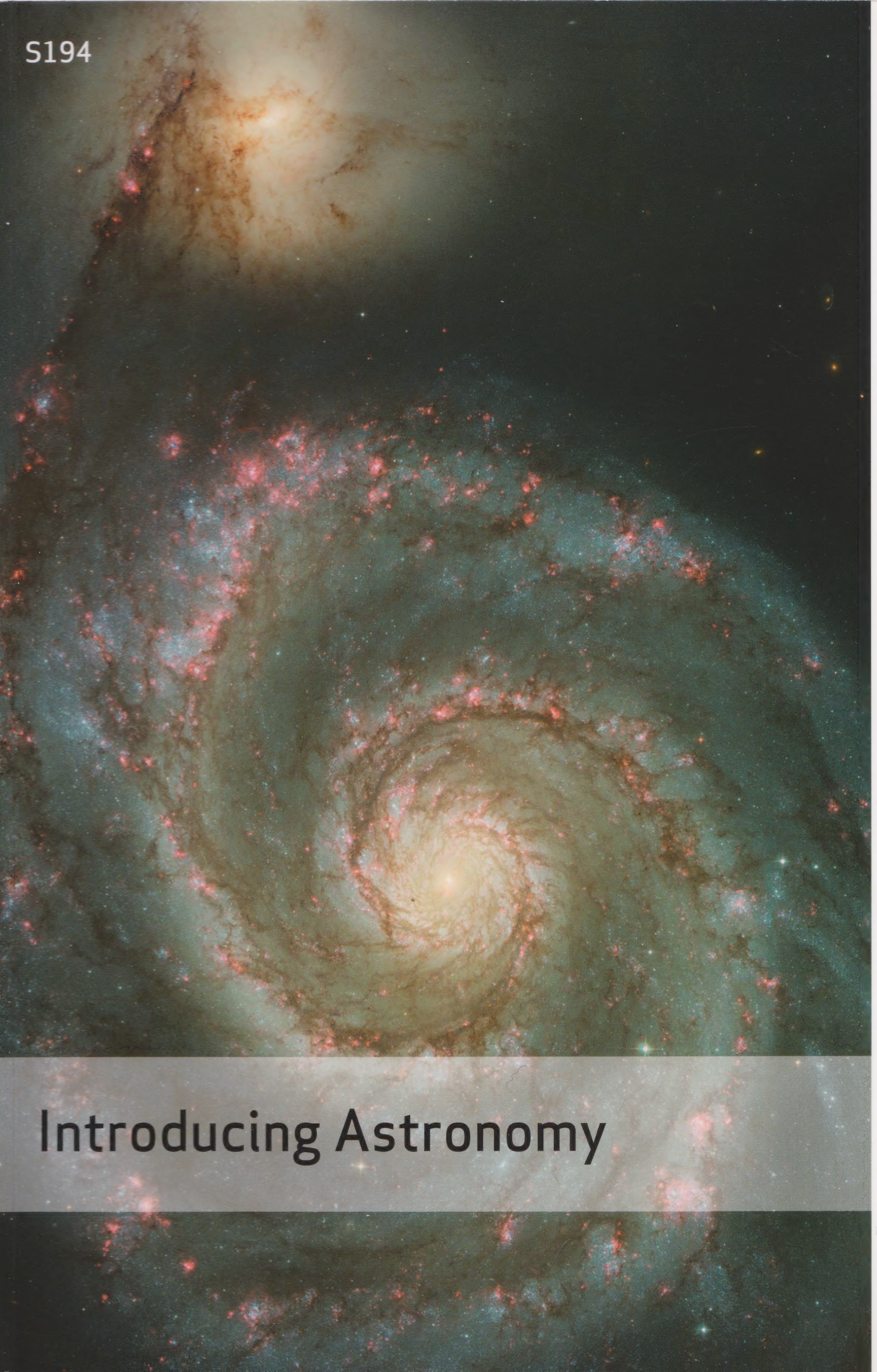

Introducing Astronomy

Science Short Course

The Open University

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Simon Green and Robert Lambourne

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Contents

Introduction

1

Astronomy is the study of the celestial bodies and the regions of space that separate them. It is a vast subject: quite literally as big as the Universe. It encompasses planets such as the Earth, stars such as the Sun, galaxies such as the Milky Way, and even vast gatherings of thousands of galaxies such as the Local Supercluster in which we live and which represents about one-tenth of a millionth of the entire visible Universe. Figure 1.1 gives you a glimpse of some of these celestial objects and tries to convey a sense of the scale of the journey that awaits you.

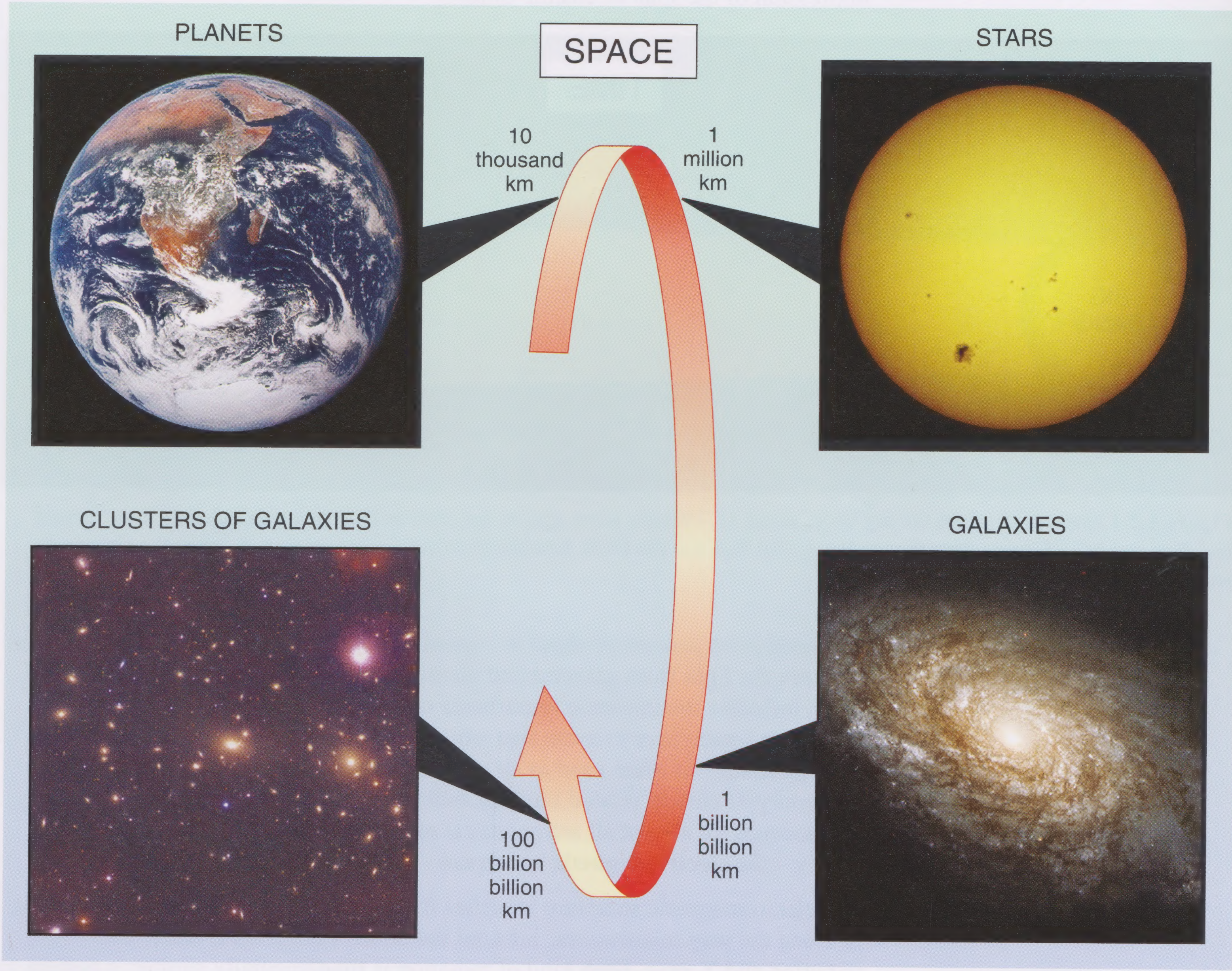


Figure 1.1 A planet, a star, a galaxy and a vast cluster of galaxies: each object has its own characteristic size scale, ranging from thousands of kilometres for a planet to more than one hundred billion billion kilometres for a supercluster of galaxies. (A billion is one thousand million.)

This book, together with the materials on the CD-ROM and other resources in the course S194 *Introduction to Astronomy*, provides a very brief introduction to the subject. Even so, it will take you not only on a journey through space but also on a trip through time. Current views of different parts of the Universe offer a wonderful spectacle, but all astronomers know that, as they peer across vast cosmic spaces, they also look back over great reaches of cosmic time. This is an unavoidable consequence of the finite speed of light. The light that we see today from the most distant observable galaxies was emitted over 12 billion years ago, and the earliest signals of any kind that can be detected (a particular kind of microwave radiation, sometimes referred to as the 'afterglow of the big bang') are believed to have originated over 13 billion years ago. Figure 1.2 gives an impression of the span of cosmic time.

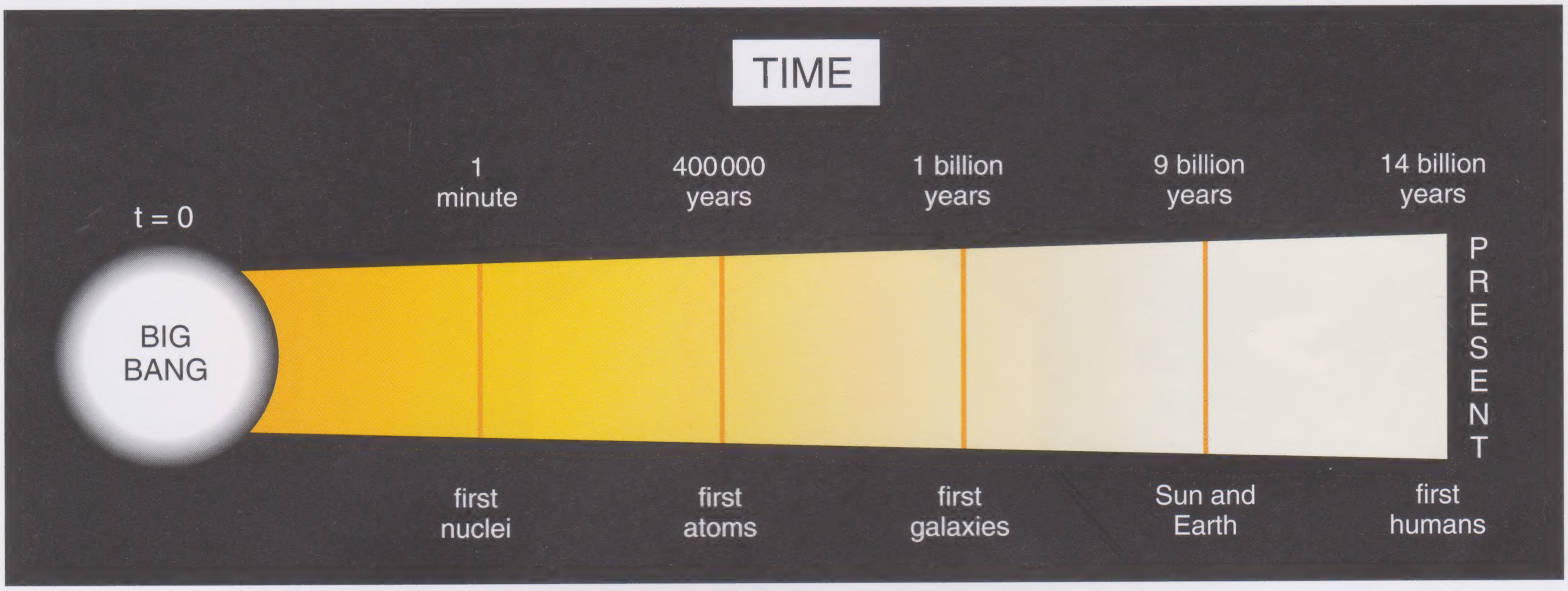


Figure 1.2 Cosmic time, from the big bang, about 13.7 billion years ago, to the present. The first galaxies may have formed less than one billion years after the big bang. The Sun and the Earth formed about 4.6 billion years ago, when the Universe was about 9 billion years old.

The need to be concerned about the speed of light, and even about the distinction between the light from galaxies and the microwaves associated with the big bang, indicates the immense importance of *radiation* to astronomers. The term **radiation** – used here to mean that which is radiated from a source and travels through space – is often used as an abbreviation for **electromagnetic radiation**: the family of closely related kinds of radiation, including light and microwaves, that account for almost all astronomical observations. The full range of this family – the **electromagnetic spectrum** – is shown in Figure 1.3.

The electromagnetic spectrum stretches from radio waves to gamma rays, taking in along the way microwaves, infrared radiation, visible light, ultraviolet radiation and X-rays. Each kind of radiation is fundamentally similar: a pattern of fluctuating electric and magnetic disturbances that can effectively tumble over one another to travel through empty space at the speed of light, about 300 000 kilometres per second.

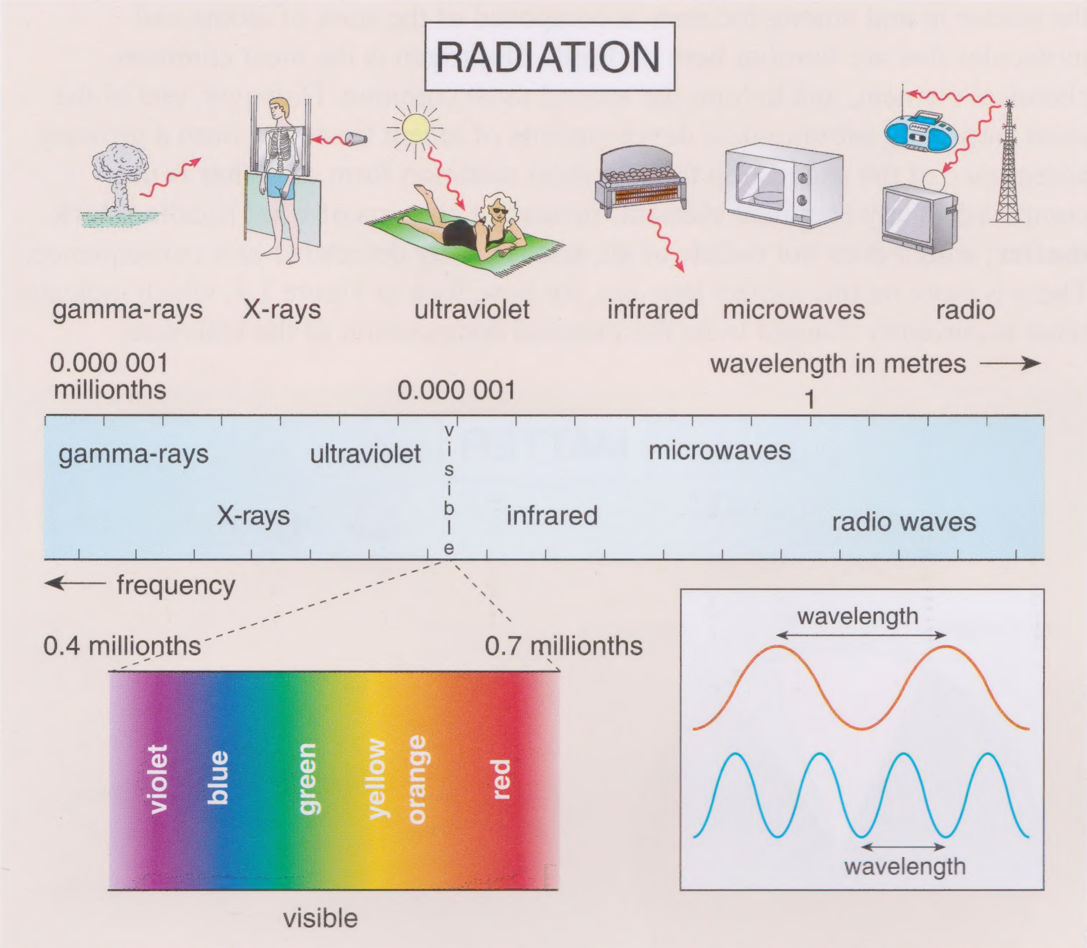


Figure 1.3 The electromagnetic spectrum: a family of closely related types of radiation that includes light, microwaves and much more. The various kinds of electromagnetic radiation can be distinguished by their *wavelength*. In the case of visible light, different wavelengths are perceived as different colours but there is no fundamental distinction between the parts of the spectrum.

Each type of electromagnetic radiation takes the form of a travelling wave, created from the varying strength and direction of the electric and magnetic disturbances at every point along the radiation's path. The waves associated with any part of the electromagnetic spectrum may be characterised by their **wavelength** (see Figure 1.3), which is the distance between neighbouring peaks of the travelling wave.

X-rays, which are emitted naturally by many energetic astronomical sources, cover the range of wavelengths from about one hundredth of a billionth of a metre to about ten billionths of a metre, while visible light covers the narrow range from violet-coloured light, with a wavelength of about 0.4 millionths of a metre, to red-coloured light, with a wavelength of about 0.7 millionths of a metre. Microwave wavelengths range from about one thousandth of a metre (i.e. one millimetre) to about one tenth of a metre (0.1 metre). Thanks to space telescopes and sophisticated radiation detectors, all parts of the electromagnetic spectrum can now be used for astronomical observations, and each kind of radiation has contributed to the growth of astronomical knowledge.

Radiation is very important in its own right but, for many astronomers, it is simply the means of finding out about the sources of the radiation. Those sources, mainly the stars and galaxies, together with the clouds of gas that surround them, are ultimately composed of *matter*. So matter is also of interest to astronomers, and its many forms of behaviour must be properly taken into account if the signals received from space are to be fully understood. Much of

the matter in and among the stars is composed of the sorts of atoms and molecules that are familiar here on Earth. Hydrogen is the most common chemical element, and helium the second most common. However, one of the most surprising astronomical developments of recent times has been a growing acceptance of the suggestion that the most common form of matter is not composed of any chemical element. Instead, it consists of what is called **dark matter**, which does not radiate at all, and is barely detectable as a consequence. There is more on this subject later but, for now, look at Figure 1.4, which indicates what is currently thought to be the material composition of the Universe.

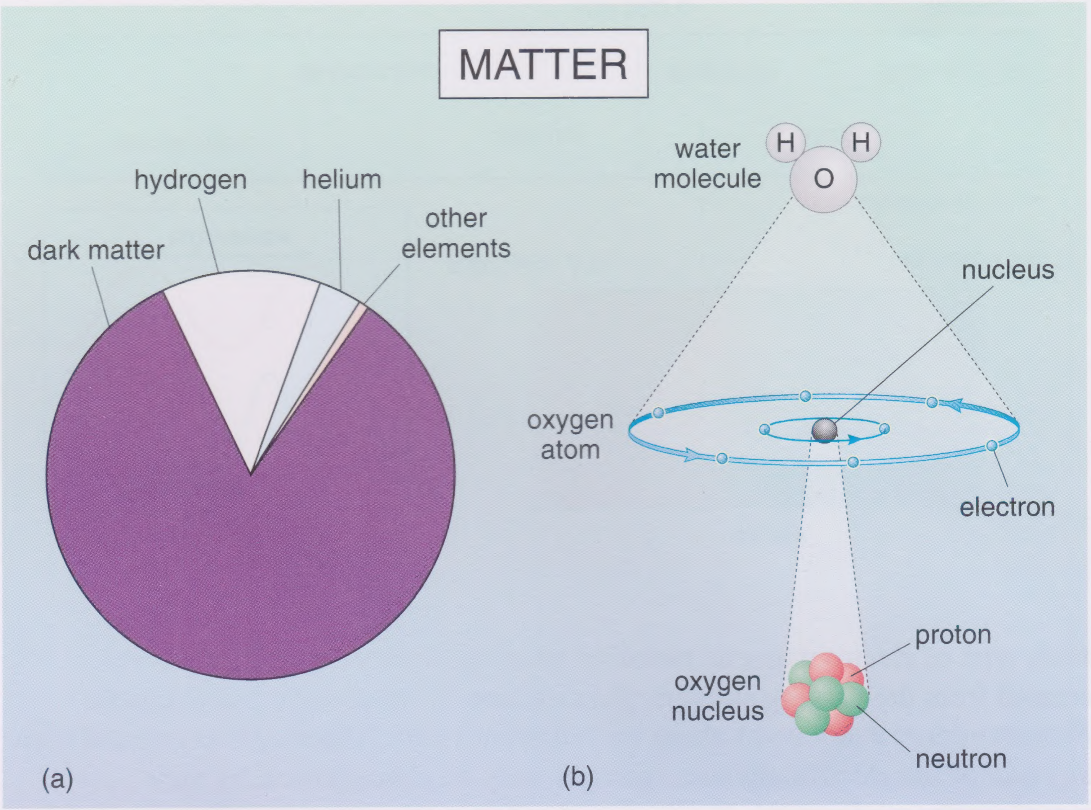


Figure 1.4 The matter in the Universe. (a) Chemical elements account for less than about one-sixth of all matter. The majority is believed to consist of non-luminous 'dark matter', the nature of which is still uncertain. (b) The chemical elements consist of atoms in which particles called *electrons* orbit a central nucleus composed of *protons* and *neutrons*. The electrical attraction between negatively charged electrons and positively charged protons holds the atom together but, in many astronomical settings, the majority of the atoms have lost one or more of their electrons.

You may wonder how astronomers discovered that hydrogen is the most common chemical element and helium the next most common. The answer depends, at least partly, on the remarkable amount of information that can be obtained from the study of *spectra*. Radiation from a bright body, such as a planet, star or galaxy, naturally consists of a mixture of many wavelengths, often covering an almost continuous range. When referring to the **spectrum** of a particular body we usually mean the range of wavelengths coming from that body, along with additional information about the 'amount' or 'intensity' of the radiation in any narrow band of wavelengths (a measure of the energy carried by that band of wavelengths).

The spectrum of visible light from a celestial body can be examined by passing the light from that body through a narrow slit and then allowing it to pass through a triangular glass prism (see Figure 1.5). The prism *disperses* the light, causing slightly different wavelengths to travel in slightly different directions. As a result, the light spreads out to form a rainbow-like band ranging from red to violet. The variation of intensity with wavelength is revealed by the relative brightness of the different parts of the spectrum.

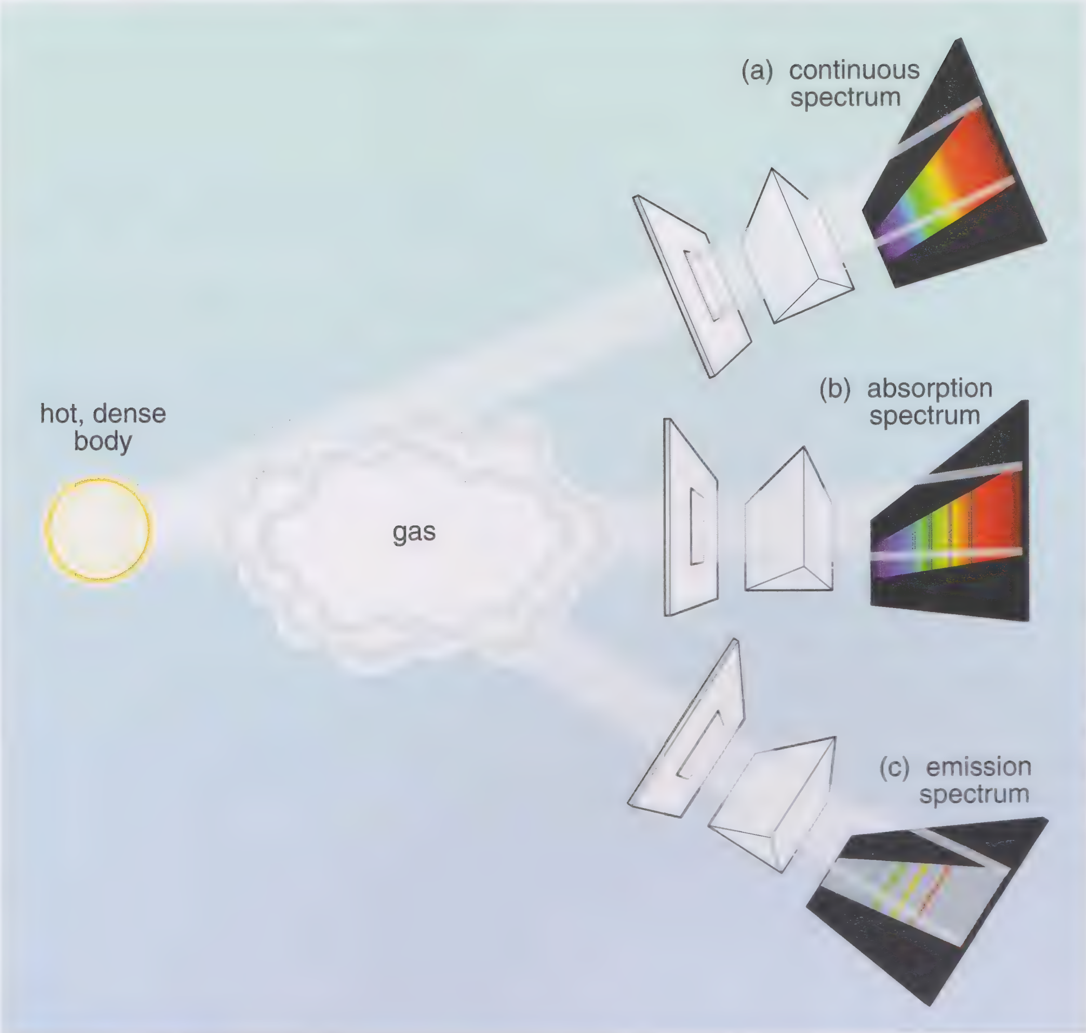


Figure 1.5 Three kinds of spectra. (a) The unbroken, continuous spectrum of a hot, dense body. (b) The absorption spectrum when light with a continuous spectrum passes through a cloud of gas. (c) The emission spectrum of light radiated from a cloud of gas.

The visible spectrum of a hot, dense body consists of a continuous band of colours (Figure 1.5a). A relatively cool body will emit mainly red light, a hotter one mostly yellow light, and a very hot body predominantly blue or violet light but, in all cases, the light forms a **continuous spectrum**. If, however, a cloud of gas is interposed between the source and the observer, the atoms in that cloud will absorb certain characteristic wavelengths, producing a corresponding pattern of relatively dark 'absorption lines' that cross the spectrum, destroying its smooth continuity (Figure 1.5b). The resulting **absorption spectrum** provides a sort of chemical fingerprint of the cloud that a sufficiently skilled scientist can use to determine the composition of the gas cloud. The energy carried by the 'missing' wavelengths is absorbed by the cloud, but only temporarily. The cloud will soon lose that energy, often by emitting just the same wavelengths of radiation that it absorbed earlier. However, the emitted radiation generally goes in all directions, so it may be seen by observers who are not looking towards the hot, dense body (Figure 1.5c). The spectrum seen by such observers consists of relatively bright 'emission lines' against a generally dark background and is called an **emission spectrum**. It too can be used to determine the composition of the gas cloud.

By observing the spectra of a wide range of celestial bodies, astronomers can deduce the relative abundances of the chemical elements, and much else besides. As you will learn later, spectra are also used to study the movements of astronomical bodies and even to deduce details about their temperatures, pressures and magnetic fields. Spectra are estimated to account for more than 90% of all available astronomical information; this estimate emphasises the intimate linkage between matter and radiation.

Space, time, matter and radiation are the crucial ingredients of modern astronomy. As you work through this course, learning about particular astronomical bodies and the processes that drive them, you will also gain insight into these four basic ingredients. It will be a colourful and spectacular journey, a treat for the eye but also a feast for the mind. The visual splendour of the astronomical Universe is attractive to many people, but it is the richness and depth of the concepts involved that gives the subject its scientific fascination.

The course team hope that you will enjoy this introduction to astronomy, and that you emerge from it with a better understanding of the physical Universe, and a fuller appreciation of the night sky. The team also hope that this brief excursion will show you the enormous breadth of the subject and possibly whet your appetite for further exploration. In such a brief trip you cannot hope to cover the whole subject – but at least you can make a start.

The Sun

2

2.1 Introduction

For astronomers, the **Sun** is fascinating because it is our nearest **star**. By studying the Sun, they can gain an insight into the workings of the other millions of stars that are visible in the night sky. Learning that the Sun is a star can be a little surprising. After all, the Sun is a brightly glowing, yellow object – so bright that it is dangerous to look at it directly, and so hot that we can feel its radiation warming the whole Earth. Stars, on the other hand, are mere silvery pinpoints of light that are visible only against the darkness of the night sky and with no discernible heating effect on Earth. How can they possibly be the same sort of object? The key to the answer lies in their *distances*.

In astronomical terms, the Sun is relatively close, being only about 150 million kilometres (93 million miles) from Earth. The stars that are visible at night are much further away: the nearest is about 40 *million million* kilometres from Earth, and most are much more distant than that. Imagine looking at a glowing light bulb first from very close up and then from a much greater distance. Close up, you would see the shape of the bulb but, from far away, it would be just a point of light.

2.2 Observing the Sun

Safety warning

Never look directly at the Sun, either with the unaided eye or through spectacles, binoculars or a telescope. You risk permanently damaging your eyes if you do so.

2.2.1 The Sun at visible wavelengths

The Sun is seen as a blindingly bright, yellow object in the sky. The part of the Sun that you normally see is called the **photosphere** (meaning 'sphere of light'); this is best thought of as the 'surface' of the Sun, although it is very different from the surface of a planet such as Earth. Its diameter is about 1.4 million kilometres, making the Sun's volume roughly one million times that of the Earth. The photosphere is not solid. Rather, it is a thin layer of hot gaseous material, about 500 kilometres deep, with an average temperature of about 5500 °C (degrees Celsius).

Detailed studies of the body of the Sun usually require special equipment. However, the natural phenomenon known as a **total eclipse of the Sun** provides an opportunity to gain further insight into the nature of the Sun (see Figure 2.1 overleaf). A total eclipse happens when the Moon passes in front of the Sun and blocks out the bright light from the photosphere.

When the Moon just eclipses the bright photosphere, it is often possible to see part of a narrow, pink-coloured ring that encircles the Sun. This is the **chromosphere** (meaning 'sphere of colour'), the lower or 'inner' part of the Sun's atmosphere. It is actually another layer of gaseous material, a few

Figure 2.1 A total eclipse of the Sun, revealing the inner and outer parts of the Sun's atmosphere, the chromosphere and the corona.

thousand kilometres thick, that sits on top of the photosphere. The lower parts of the chromosphere are cooler than the photosphere, while the higher parts are considerably hotter, but the chromospheric material is so thin that it emits relatively little light, and is therefore unseen under normal conditions.

As a total solar eclipse proceeds, a third part of the Sun is seen – the **corona** (meaning 'crown'). This is the extremely tenuous (i.e. thin) upper atmosphere of the Sun that extends out to several times the Sun's photospheric radius. The corona seems to be composed of streamers or plumes, but its shape changes from eclipse to eclipse, although it will not usually show any changes during the few minutes of totality that characterise a typical total eclipse. The corona is very hot (temperatures of several million degrees Celsius are not unusual) but it is so thin that its pearly white light is very faint compared with the light from the photosphere.

Answering in-text questions

Throughout this book there are in-text questions (marked by a ●), which are immediately followed by their answers (marked by a ●). To gain maximum benefit from these questions you should cover up the answer until you have thought of your own response. You will probably find it helpful to write down your answer, in note form at least, before reading the answer in the text.

● The corona may be faint, but it does glow. Why are we not normally aware of the Sun's corona?

● The bright light from the Sun's photosphere is scattered by the Earth's atmosphere. This makes the sky blue and generally rather bright. As a result, we cannot observe the much fainter light from the corona (rather as the light from a dim torch is unnoticeable on a bright sunny day).

Sometimes in eclipses observers also see **prominences** – great spurts of hot material at the edge of the Sun, extending outwards from the solar surface for many thousands of kilometres. Prominences and the changing shape of the corona indicate that the Sun is an active body, not just a quietly glowing source of light. There is further evidence of this in the S194 Image Bank, which you will look at shortly. This will introduce you to other features of the visible Sun, including the seething pattern of **granules** seen all across the photosphere, and the relatively cool **sunspots** that appear as small dark patches on the photosphere. Individual granules come and go in a few minutes, often to be replaced by other granules. Sunspots are larger and longer-lived, typically surviving for a week or so, and sometimes for many weeks. The longer-lasting sunspots can be photographed repeatedly as they cross the face of the Sun. They can even be used to investigate the rate at which the Sun rotates.

Activity 2.1 Consulting the Image Bank

15 minutes

From your computer, access the S194 Image Bank on the CD-ROM and examine the images in the section on the 'visible Sun'. Read the captions carefully, paying particular attention to any reference to sunspots. When you have completed this part of the activity, search the bank using the key word 'sunspot' to see whether there are any relevant images beyond those in the section specifically devoted to the visible Sun. Briefly examine any images that you find. ◀

2.2.2 Beyond visible light

During the twentieth century, astronomers extended their capabilities by developing telescopes and detectors that were sensitive to radio waves, microwaves, infrared and ultraviolet radiation, X-rays and gamma rays. All these forms of electromagnetic radiation, along with visible light, are emitted by the Sun.

The *electromagnetic spectrum* was introduced in Chapter 1, but this is a good point at which to examine it in more detail and to review some of its features. Referring back to Figure 1.3, note that the wavelength values are marked in metres but only some of the marks are labelled. The marks go up in 'times ten' steps so, to the right of the 1 metre mark, the first (unlabelled) mark indicates a wavelength of 10 metres (10 m), the next 100 m and the third 1000 m. Going to the left of the 1 metre mark, the next mark is 0.1 m, then 0.01 m (which is 1 centimetre or 1 cm for short), 0.001 m (1 millimetre or 1 mm), and so on. Going further to the left involves putting more and more zeroes after the decimal point, so the wavelengths are sometimes measured in *micrometres* – millionths of a metre. One micrometre is 0.000 001 metres. (As you will see in Chapter 3, very small and very large numbers can be written in a more convenient way, which avoids writing strings of zeroes.)

- What is the definition of the wavelength of an electromagnetic wave?
- It is the distance between successive peaks of the wave. (See Figure 1.3 if you need a reminder.)
- Roughly, what is the wavelength of visible light?
- It is about 0.000 001 metres (actually, 0.000 000 4 to 0.000 000 7 metres).

- What type of electromagnetic radiation has the longest wavelength? What, approximately, is its wavelength range?
- Radio waves are the longest: in Figure 1.3, the shortest radio waves lie about one step to the left of the 1 m mark, which denotes a wavelength of 0.1 m. The band representing radio waves extends to the far right of the chart. The furthest mark on the right represents a wavelength of 1000 m (three steps to the right of the 1 m mark), so the figure shows that radio waves can have wavelengths of over 1 kilometre. (Such wavelengths are typical of radio stations still broadcasting in the 'long wave' band.)

2.2.3 The invisible Sun

Figure 2.2 shows an image of the Sun, taken when a huge prominence was visible (bottom left). The image was recorded using instruments that are sensitive to ultraviolet radiation rather than visible light, so the colours that you see are 'false'. They simply indicate different levels of intensity of ultraviolet radiation. The use of such false colour images is unavoidable when dealing with radiation that lies outside the range of visible wavelengths. None the less, the image shows that prominences emit copious amounts of ultraviolet radiation and are therefore observed easily at those wavelengths.

The Sun's radio waves carry much less energy than its visible light but can readily be detected with even a small radio telescope. Fortunately for us, the Earth's atmosphere shields us from the Sun's potentially harmful X-rays, so these can only be studied using telescopes put into orbit above the atmosphere.

Figure 2.2 A 'false colour' image of the Sun, taken at ultraviolet wavelengths.

A combination of ground-based and space-based instruments has enabled astronomers to observe the Sun over a wide range of wavelengths and to build up a clear picture of its various emissions.

Many solar observers are particularly interested in the Sun's **active regions** (see Figure 2.3), the nature and appearance of which depend on the locality and the wavelength being observed. When seen in the photosphere at visible wavelengths, active regions are often associated with groups of sunspots. Their counterparts in the chromosphere, sometimes observed at specific red, blue and ultraviolet wavelengths, are bright regions known as *plage* (which is French for 'beach'), while in the corona, X-ray astronomers can see transient regions of higher than usual temperature and pressure called *coronal condensations*. Active regions are generally caused by the Sun's **magnetic field**, which influences the flow of hot gaseous material on the Sun, and can sometimes rearrange itself on very short time-scales (seconds or minutes). Such sudden changes to the magnetic field in the corona are thought to be responsible for **flares**, one of the most energetic of all solar phenomena. Flares emit radiation of all wavelengths, from radio waves to gamma rays. Much of the energy is emitted very quickly at the start of the flare, although the flare will typically continue to radiate for several hours, even lasting a day in exceptional cases. Energetic particles are also emitted during a flare (fast-moving protons and electrons for instance), which certainly reach the Sun's surface and, sometimes, even the Earth.

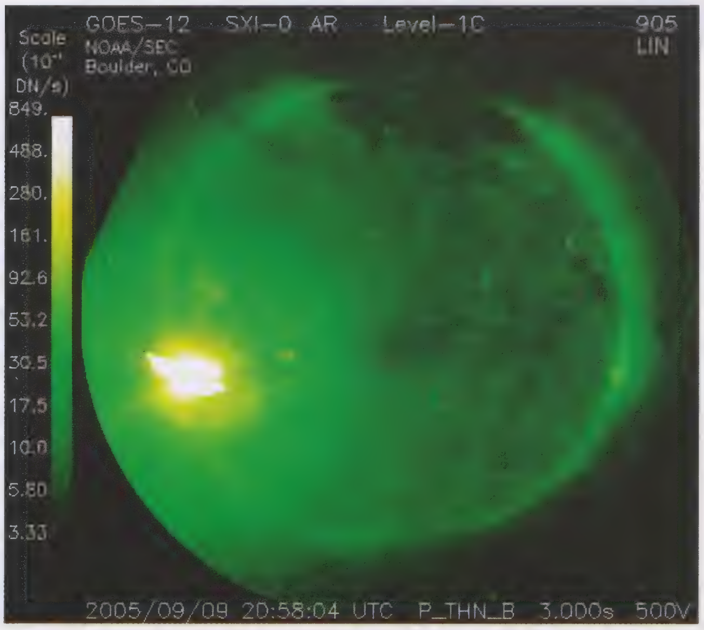


Figure 2.3 An active region of the Sun, represented by a powerful flare (seen here as X-rays) associated with a large sunspot group.

Activity 2.2 Examining images of the invisible Sun

20 minutes

Images from a variety of telescopes, representing various wavelengths of 'invisible' radiation, are included in the 'invisible Sun' section of the S194 Image Bank. Some of these images enhance astronomers' knowledge of particular solar features (such as prominences or sunspot groups), while others help them to observe particular regions (such as X-ray images of the corona or ultraviolet images of the chromosphere). You should examine those images now, taking care not to be misled by their use of false colours. ◀

Using the internet for updates

The Sun is constantly being watched from a variety of observatories. You can usually find recent images by searching the internet, using terms such as 'solar image' or modifications such as 'solar image, X-ray'. Some particularly useful websites are given in the S194 Data Bank. These sites have been chosen partly because of their reliability. By all means look for other websites but be aware that there are few guarantees of quality or reliability on the internet. Always ask yourself how much you should rely on any particular source. University websites are generally fairly reliable but even there you should exercise caution.

2.3 Inside the Sun

To account for its brightness and activity, the Sun must contain a power source. However, the nature of that power source was a great puzzle in the nineteenth and early twentieth centuries. Fossil records and ideas about evolution were beginning to provide firm evidence that the Earth must be at least hundreds of millions of years old, rather than thousands of years as was previously thought, and the Sun must be at least as old as the Earth. The only fuels known at the time were coal, wood, oil, gas, and so on. It was fairly easy to calculate that, even if the Sun were made entirely of one of these fuels, and could get the necessary oxygen from its surroundings, it could burn for only a few thousand years at most while producing its current output of heat and light – not nearly long enough to sustain life on Earth over millions of years.

The problem of the Sun's fuel baffled many of the world's best scientists until **nuclear reactions** were discovered in the early twentieth century. Such reactions provided a totally new type of energy source. Rather than burning like coal or gas, nuclear reactions need no oxygen and produce vastly more heat and light for a given amount of fuel. Nuclear reactions give 'atomic' weapons their great destructive power but are harnessed more productively in electricity generation. The type of reactions that power the Sun – so-called *fusion reactions* involving hydrogen – are similar to those that occur in a hydrogen bomb, but in the Sun they proceed steadily rather than as an explosion.

Figure 2.4 Sir Arthur Eddington (1882–1944), astronomer and mathematician: one of the first astronomers to understand the internal constitution of stars.

The British astronomer Arthur Eddington (Figure 2.4) calculated that, if the Sun were made mainly of hydrogen undergoing nuclear reactions, it could last for millions of years while producing a more-or-less steady heat and light output. Furthermore, its outward appearance would closely resemble that of the actual Sun. We now know that hydrogen nuclear reactions will sustain the Sun for about ten thousand million years. The Sun is currently about half-way through the hydrogen-fuelled phase of its life.

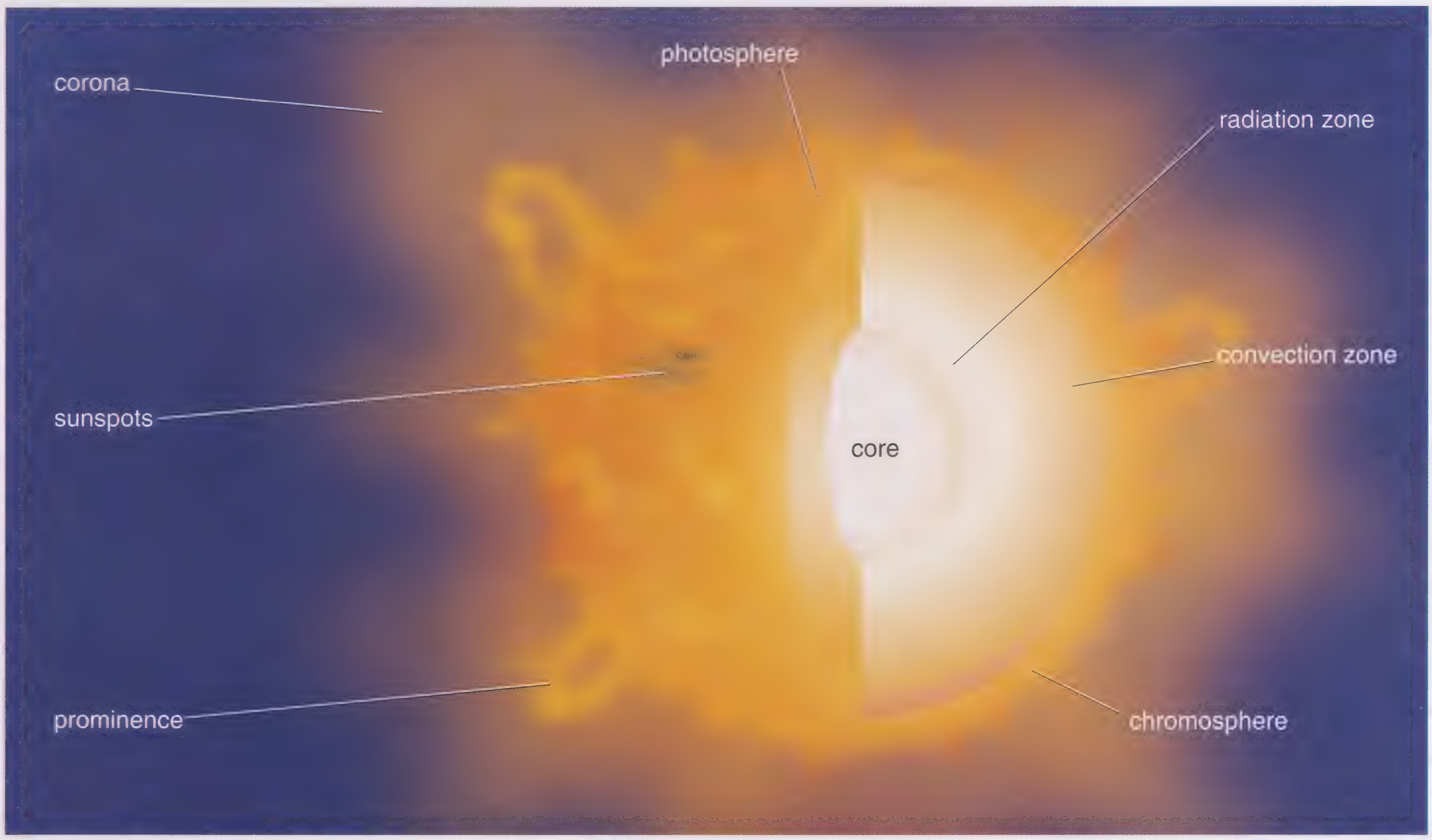
Everything that is known about nuclear reactions is based on experiments performed in laboratories on Earth. Eddington's great triumph was being able to take that knowledge and work out what would happen if nuclear reactions happened on a far larger scale than was possible on Earth, and to relate his deductions to what was known about the Sun. This example illustrates an

important feature of astronomy: everything that is known about the Universe beyond our Earth and Moon (apart from a few planets that space probes have visited) must be deduced by observing from a very great distance. Astronomers have two main strands to their quest to understand such distant objects. One strand involves the observations themselves: studying the appearance and movement of distant objects and analysing the radiation received from them. The other strand involves finding out how objects behave on Earth and using that knowledge to interpret and account for the observations.

Scientists have used what they know about nuclear reactions and about how very hot materials behave, together with detailed observations of the Sun, to piece together a model (that is, a mental picture) of what the Sun must be like deep inside. This is shown schematically in Figure 2.5 and described in the caption. The Sun does indeed consist largely of hydrogen and it is fluid throughout. The nuclear reactions occur only in the Sun's **core** – that is, deep in its centre – because the hydrogen fuel needs to be at a temperature of over 10 million °C before nuclear reactions can begin. Energy is carried away from the core by radiation that is repeatedly absorbed and re-emitted as it travels through the **radiative zone**. Closer to the surface, energy is transferred by a different process, known as *convection*, in which material, heated from below, expands and floats upwards, displacing cooler material that sinks downwards through the **convection zone**.

As rising columns of hot material approach the top of the convection zone, the material above becomes thinner, increasing the chance of any emitted light escaping into space. This 500-kilometre thick region constitutes the photosphere,

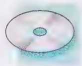
Figure 2.5 The solar interior. Temperature and density increase rapidly with depth inside the Sun, but only in the central core are the conditions right for nuclear reactions to occur. Beyond the core there are zones where energy is transported to the surface by processes involving radiation and convection (hot material rises while cooler material sinks to replace it).



and the rising and falling columns of solar material account for the seething pattern of granules mentioned in Section 2.2.1.

Our understanding of the solar interior depends very much on our ability to understand the laws of physics that govern its behaviour. However, there are observations, based particularly on **solar neutrinos** and **solar oscillations**, that support and guide our theories. These are explored in the section of the S194 Image Bank devoted to 'the solar interior', which you should look at in the next activity.

Activity 2.3 Describing the Sun



30 minutes

At the start of this chapter, the Sun was referred to as a 'blindingly bright, yellow object'. From what you have read and studied so far, you now know rather more about the Sun than that simple description. Spend a few minutes looking through the text and the relevant pictures and captions from the S194 Image Bank, including those concerning 'the solar interior'. Summarise what you have learned about the Sun's appearance and about its interior. Your summary should be in the form of a labelled sketch (maybe based on Figure 2.5). Try to make your summary as precise as possible: for example, include sizes and temperatures of the various parts of the Sun where you can. ◀

2.4 Measuring the Sun

Section 2.2 referred to observations that can only be made using sophisticated telescopes, but this section turns to an observation you can do yourself. There are two reasons for this: one is to give you experience in scientific measuring and the other is to introduce some terminology that astronomers use frequently.

2.4.1 Angular size

The image in Figure 2.1 was taken during a total eclipse of the Sun, in which the Moon blocked out light from the Sun's photosphere, enabling the chromosphere and the corona to be seen. This happens because of a remarkable coincidence. The Sun is very much bigger than the Moon – about 400 times bigger in diameter – but it is also very much further away, by almost exactly the same factor. This means that the Sun and the Moon *appear* the same size in the sky: that is, the Sun and the Moon have the same **angular size**. Figure 2.6 illustrates this idea by showing lines drawn from an observer's eye to the extreme edges of objects at various distances. The angle between the lines determines the angular size of the objects, which would be 10° in all three cases, according to the shown observer. Angular size thus depends on an object's actual size and its distance from the observer's eye.

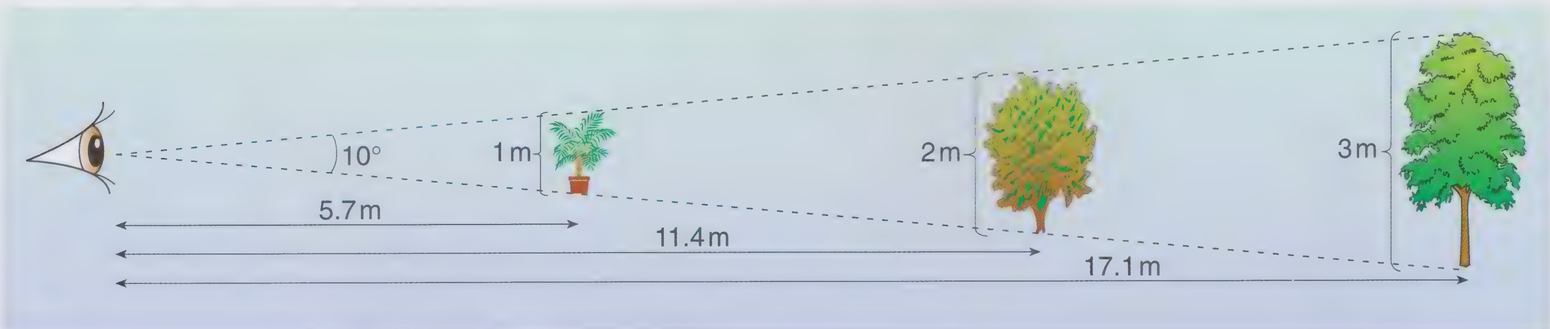


Figure 2.6 The observed angular size of an object depends on the size of the object and its distance from the observer.

You are probably familiar with angles measured in degrees (360° for a full circle, 90° for a right angle, and so on). However, although the objects studied by astronomers are very large, they are at such vast distances that their angular sizes are often very small. These small angles could be written as fractions of a degree or their decimal equivalents but, in practice, subdivisions of degrees are used, known as minutes of arc (or *arcmin*) and seconds of arc (or *arcsec*). A degree can be divided into 60 minutes of arc, and a minute of arc can be further divided into 60 seconds of arc. A single tick mark is used to represent arcmin, so 1/60 of a degree is written 1′. A double tick mark denotes arcsec, so 1/3600 of a degree (1/60 of an arcmin) is written 1″.

Angular size is a very useful quantity in astronomy, since angular sizes are *very* much easier to measure than actual sizes because they refer simply to how large an object appears in the sky. The Sun and the Moon both have an angular size of about half a degree, which is about 30 arcmin or 30′.

- How would you *define* the angular size of the Moon?
- It is the angle between two imaginary lines drawn from an observer's eye to the extremities of the disc of the Moon. (More formally, it is the angle *subtended* at the eye of the observer by the *diameter* of the Moon.)

2.4.2 Angular size, actual size and distance

The angular size of an object is determined uniquely by its actual size and its distance from the observer. For an object of fixed size, the *larger* the distance, the *smaller* the angular size. For objects at a fixed distance, the *larger* the actual size of an object, the *larger* its angular size. For objects with small angular sizes, such as typical astronomical objects, the precise relationship between angular size, actual size and distance is well approximated by the equation:

angular size = (actual size ÷ distance).

However, when using this equation you must be very careful about the units in which quantities are measured. If the actual size and the distance are measured in the same units (metres or kilometres, or anything else as long as it is used for both quantities), the angular size that you calculate will be in measured units called *radians*. A radian is equal to a little more than 57° so, in order to obtain angular sizes in degrees, the following approximation can be used (as long as the angular size is not too great):

angular size in degrees = 57 × (actual size ÷ distance).

The next question asks you to apply this expression to Figure 2.6.

- Calculate 57 × (actual size ÷ distance) for each of the objects in Figure 2.6.
- The values are 57 × (1 m ÷ 5.7 m), 57 × (2 m ÷ 11.4 m), 57 × (3 m ÷ 17.1 m), which is 10° in each case (as expected).

Units, numbers and physical quantities

Much of astronomy concerns quantities such as temperatures, distances, diameters and angular sizes. In all of these cases, units of measurement are important. Physical quantities are generally the result of multiplying

together a number and a unit of measurement. Thus a distance such as 5.2 kilometres is really the result of multiplying the number 5.2 by the unit of distance known as the kilometre. There are many units of measurement in common use, so, whenever you quote the value of a physical quantity, you should always take care to include the unit as well as the number multiplying that unit. It is no use being told that a distance is 5.2 if you don't know whether that means 5.2 centimetres or 5.2 kilometres. The unit is at least as important as the number.

In scientific work there are several internationally agreed conventions for the definition of units and the way in which units should be used and represented when writing down the values of physical quantities. The most widely adopted system of units is known as SI, which stands for Système International. This is based on seven carefully defined units that include the metre (for length), the second (for time) and the kilogram (for mass). The other four base units relate to luminous intensity (i.e. brightness), quantity of matter, electric current and temperature, the unit of which is the same size as the degree Celsius but starts from a different zero value and is called the kelvin.

The recognised abbreviations for the metre, the second and the kilogram are m, s and kg, respectively. In all cases, units should be written in the singular form, so it should really be 5.2 kilometre or 5.2 km, rather than 5.2 kilometres, and certainly never 5.2 kms, since that might be misinterpreted as 5.2×1 km $\times 1$ s.

In calculations, units should be treated in the same way as numbers, so the result of dividing 6.0 km by 3.0 s is 2.0 km/s, which can be read as 2.0 kilometre per second.

Units, such as km/s, that result from combining the *base units* are called *derived units*. The most common derived units are sometimes given their own names and symbols. The angular unit known as a radian is an example, since angular size can be equated to the result of dividing one length (a diameter) by another length (a distance). The more familiar unit of angle – the degree – is said to be a *supplementary unit* since it is defined as a specific fraction (a little less than 1/57) of a radian.

Figure 2.7 A partial eclipse of the Moon.

To do the next activity, you need to know that the Moon's diameter is 3476 km. You may wonder how this can be measured from the Earth. In principle, it is a surprisingly easy measurement to make. First, you have to find the diameter of the Earth, which can be worked out by measuring how much its surface curves. You may be surprised to learn that this measurement was made in about 235 BC by the Greek astronomer Eratosthenes, and that his value was quite close to our modern measurement of 12 756 km (for the equatorial diameter, which is slightly bigger than the polar diameter). The sizes of the Earth and the Moon can be compared by looking at the Earth's shadow on the Moon's surface during a partial eclipse of the Moon (see Figure 2.7). A careful measurement of this kind reveals that the Earth's diameter is 3.67 times that of the Moon.

Activity 2.4 The distance to the Moon

30 minutes

This activity needs to be done when the Moon is clearly visible in the sky. (It need not be done at night and, in fact, can be easier in the day or at twilight.) DO NOT ATTEMPT THIS ACTIVITY ON THE SUN.

You will need the following items:

- a selection of coins (e.g. 1p, 5p and 10p);
- a straight rod (e.g. a piece of dowelling or a garden cane) at least 2 m long;
- a tape measure at least 2 m long;
- a ruler marked in centimetres and millimetres;
- some Blu-Tack® or plasticine;
- a pocket calculator.

Set up an arrangement with a coin fixed to a rod so that the coin just 'eclipses' the Moon. Figure 2.8 shows one possible set-up.

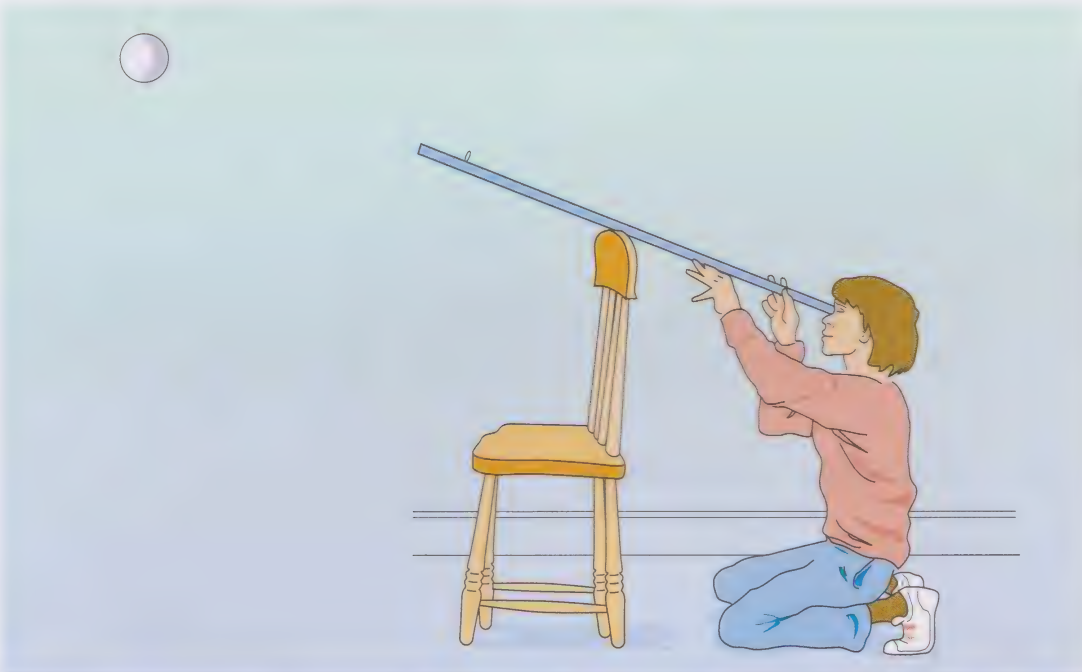


Figure 2.8 One possible arrangement for eclipsing the Moon.

Observing from one end of the rod, try different coins until you find one that is the right size to eclipse the Moon when fixed somewhere on the rod. Then adjust the position of the coin until it *just* blocks your view of the Moon. (This is less easy than it sounds, as there will always be some haze visible around the edge of the coin – try to get the best match.)

Measure the distance from the coin to the end of the rod where you have placed your eye, and measure the coin's diameter. Record your values here.

Diameter of coin = ... mm

Distance of coin = ... mm

You now have the measurements that will enable you to calculate the angular size of a coin that has the same angular size as the Moon.

Use your two measurements on the coin to calculate its angular size in degrees, using the formula introduced earlier, adapted to the current case, i.e.:

angular size of coin = 57° × (diameter of coin ÷ distance of coin) = …………

Your answer should be about half a degree (0.5°). Any value between 0.4° and 0.6° is fine. This is also your measurement of the angular size of the Moon. So, write down:

angular size of Moon in degrees = ………

The next step is to calculate the *distance* to the Moon. Just as for the coin:

angular size of Moon = 57° × (diameter of Moon ÷ distance of Moon).

This equation can be rearranged to give:

distance of Moon = 57° × (diameter of Moon ÷ angular size of Moon in degrees).

(Take this on trust if you cannot see it.) Now calculate the distance to the Moon, using your value for its angular size and 3476 km for its diameter.

Distance of Moon = 57° × (……………….…. ÷ ……………….) = …….. km.

You might like to compare your result with the accurately measured value of the Moon's distance: 384 500 km. It is unlikely that you obtained exactly this value, but you probably got something in the range 300 000 to 500 000 km, which is pretty good for a quick and fairly rough measurement. ◀

The technique used in Activity 2.4 could also be used to work out the Sun's distance if you knew its size. **However, under no circumstances should you try Activity 2.4 on the Sun because it would seriously damage your eyes.**

2.5 Chapter summary

The essential points of Chapter 2 are as follows.

1 The Sun is a star, emitting all types of electromagnetic radiation. The light that reaches Earth from the Sun comes mainly from the photosphere, although on its way to Earth it must pass through the chromosphere and the corona. Each of these parts of the Sun shows signs of magnetically driven activity.

2 Electromagnetic radiation consists of waves that can travel through empty space and cover a huge range of wavelengths.

3 The Sun is powered by nuclear reactions in its hot core which enable it to release energy steadily over thousands of millions of years. The energy released in the core is transported to the surface by radiation and then convection, passing through radiative and convection zones on the way.

4 The Sun and the Moon have approximately the same angular size when viewed from the Earth.

5 The angular size of an object depends on its actual size and its distance from the observer.

2.6 End-of-chapter questions

Question 2.1 What is the approximate wavelength range (in metres) of microwaves? ◀

Question 2.2 What are the main modes of energy transfer that participate in the transport of energy from the Sun's core to the Earth's surface? ◀

Question 2.3 In a sentence or two, explain why the problem of the Sun's fuel puzzled scientists, and say how the discovery of nuclear reactions solved the puzzle. ◀

Question 2.4 The Sun is about 150 million km from the Earth. Use information from Section 2.4 about the angular diameters of the Sun and the Moon to calculate the Sun's approximate diameter. You should note the approximate relationship:

actual size = (angular size in degrees × distance) ÷ 57°.

(Do not spend more than a few minutes trying to answer this. There is a second way of tackling this question – see whether you can find it.) ◀

Question 2.5 A large sunspot is observed to have an angular size one-twentieth that of the Sun. Taking the Sun's angular size to be 0.5°, what is the angular size of the sunspot? Express your answer in (a) arcmin and (b) arcsec. ◀

3 The planets

3.1 Introduction

This chapter stays in the neighbourhood of the Earth and the Sun. The **Solar System** consists of the Sun, nine major **planets** (although there is continued debate about the status of Pluto), some with one or more natural satellites and ring systems, **asteroids** (minor planets) and **comets**. You will find several tables containing basic data on all these bodies in the S194 Data Bank on the CD-ROM.

3.2 Survey of the Solar System

Figure 3.1 shows the layout of the Solar System. All the planets orbit the Sun in the same **prograde** direction: anticlockwise when viewed from above. Their orbits are **ellipses**, roughly in the same plane, although, except for Mercury and Pluto, they are almost circular. In Figure 3.1 the orbits are viewed from an oblique angle, which distorts their shapes. Orbits are discussed in more detail in Section 3.3.

Most of the planets spin on their axes with the same anticlockwise (prograde) sense of rotation. The exceptions are Venus, which spins very slowly backwards (**retrograde**), and Uranus and Pluto, which are tipped on their sides.

Figure 3.2 indicates the relative sizes of the major planets. Note the scale bar compared with that in Figure 3.1. The orbits of the planets cover distances of thousands of millions of kilometres, whereas Jupiter, the largest planet, is only 143 000 kilometres in diameter.

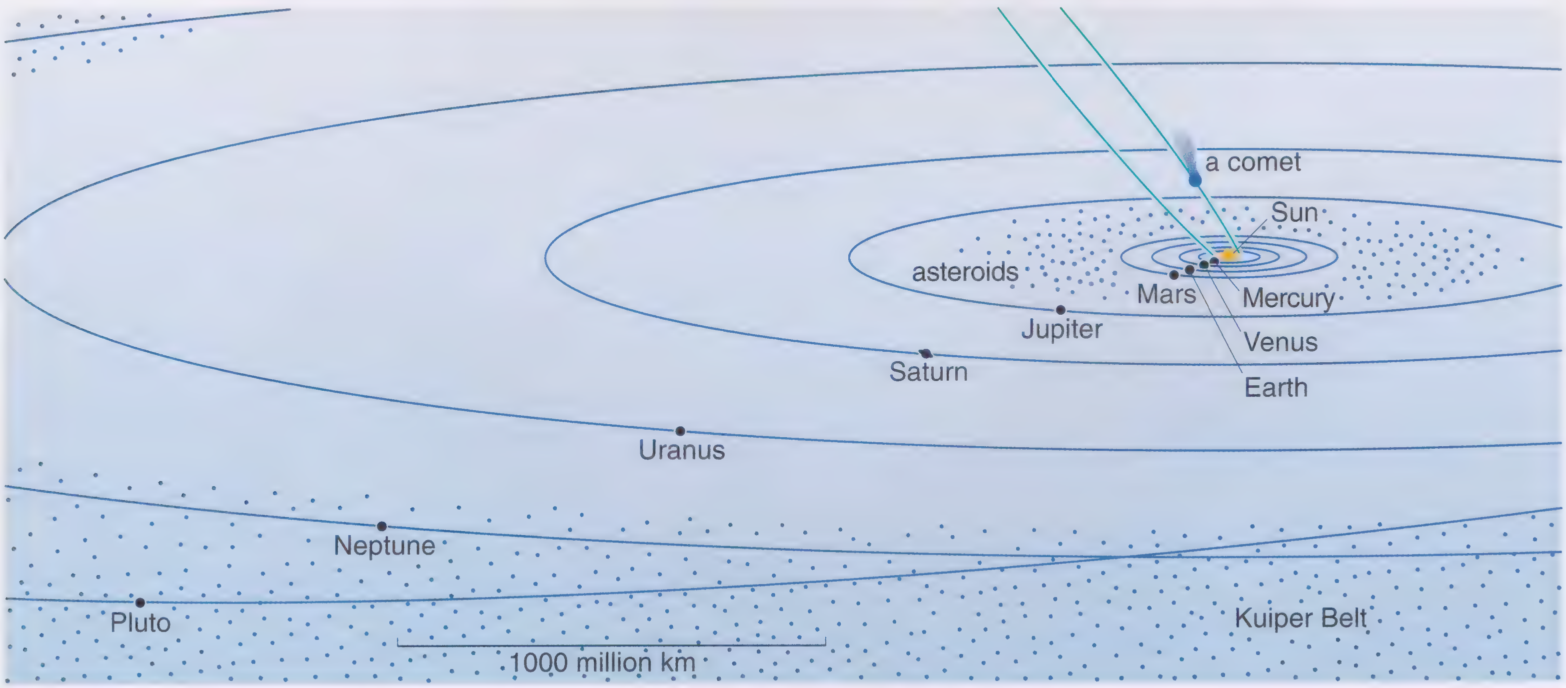


Figure 3.1 Schematic view of the Solar System showing the orbits of the nine major planets, looking obliquely southwards from outside the Solar System. Minor bodies are shown schematically: asteroids between Jupiter and Mars; trans-Neptunian objects in the outer Solar System; and the orbit of a single comet.

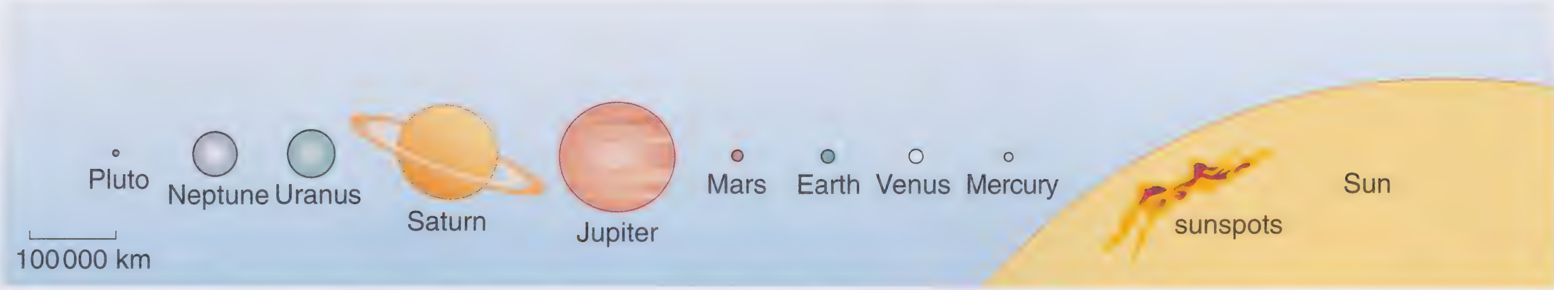


Figure 3.2 The Sun and the nine major planets, showing their true relative sizes.

Table 3.1 lists the relative sizes of the planets on a scale of 1 cm to 5000 km. On this scale, a model Sun has a diameter of about 2 m. You can get a feel for the relative sizes of the major bodies in the Solar System by representing each planet as a fruit. Note that a grapefruit (Uranus) is about ten times the diameter of a cherry (Mercury), but the volume ratio is much larger – you could fit about 1000 cherries into the volume occupied by a grapefruit.

Table 3.1 also shows the distances to the planets on the same scale. If you made a scale model of the Solar System you would not want to arrange the model planets at these relative distances! This illustrates the vast distances between the planets compared with their sizes.

Table 3.1 The sizes and distances of the planets on a scale of 1 cm to 5000 km.

Planet	Approx. diameter/km	Approx. model diameter/cm	Representative fruit	Approx. distance from Sun/million km	Approx. model distance/m
Mercury	5 000	1.0	Cherry	58	116
Venus	12 000	2.4	Plum	108	216
Earth	13 000	2.6	Plum	150	300
Mars	7 000	1.4	Cherry	228	456
Jupiter	140 000	28.0	Water melon	778	1 600
Saturn	120 000	24.0	Pumpkin	1430	2 900
Uranus	51 000	10.0	Grapefruit	2870	5 700
Neptune	48 000	9.6	Orange	4500	9 000
Pluto	2 400	0.5	Pea	5900	12 000

Scale sizes and large numbers

- The data in Table 3.1 are for a model on a scale of 1 cm to 5000 km. How much bigger is the real Solar System than the model?
- One metre is 100 centimetres, and 1 kilometre is 1000 metres, so there are one hundred thousand centimetres in a kilometre (i.e. 1 km = 100 000 cm). In 5000 kilometres there are five hundred thousand thousand centimetres – in other words, five hundred million centimetres – so the actual Solar System is five hundred million (500 000 000) times bigger than the model.

Writing down the sizes and distances of the planets involves huge numbers. Rather than writing them out in words or long strings of zeroes, there is a shorthand form known as **scientific notation**. Table 3.2 shows how it works: for example, 100 is 10×10, which can also be written as 10^2 and read as 'ten to the power of two'; 1000 is $10 \times 10 \times 10$, or 10^3; and so on. In scientific notation, five thousand can be written as 5×10^3 (five times one thousand) and five hundred million as 5×10^8, which is much more compact, and easier to read than 500 000 000 (once you are used to it). You don't have to count the zeroes because the 'power' (the small number) tells you how many there are.

Table 3.2 Powers of ten.

100 =	$10 \times 10 =$	10^2
1 000 =	$10 \times 10 \times 10 =$	10^3
10 000 =	$10 \times 10 \times 10 \times 10 =$	10^4
100 000 =	$10 \times 10 \times 10 \times 10 \times 10 =$	10^5
1 000 000 =	$10 \times 10 \times 10 \times 10 \times 10 \times 10 =$	10^6
and so on …		

In scientific notation, Mercury's diameter in kilometres could be written as 5×10^3 km, or in metres as 5×10^6 m (5 000 000 m). The convention is to write just one digit before the decimal point – writing 1.3×10^7 m as 13×10^6 m would not be incorrect, just unconventional.

- Using scientific notation, write down the diameter of Saturn in metres.
- From Table 3.1, Saturn's diameter is 120 000 km, i.e. 120 000 000 m, which is 1.2×10^8 m.

Currently, the word 'billion' is used to mean 10^9 (or 1 000 000 000), which is one thousand million.

Scientific notation is considered further in Chapter 4 – it is widely used not only in astronomy but also in many other areas of science.

The orbits of all planetary satellites lie close to the plane of their planet's equator and most travel in the same prograde direction as their planet's spin. The largest are comparable in size with the planet Mercury, whereas the smallest are little more than giant boulders. The largest of the minor bodies (asteroids, comets and **trans-Neptunian objects**) are more than 1000 km in diameter. (These objects are discussed further in Section 3.6.)

The combined mass of the planets is less than 0.2% of the mass of the Sun. For this reason the Sun dominates the Solar System in several ways. The Sun's gravitational force controls the motion of bodies within the Solar System (see Section 3.3). Its radiation has a decisive effect on the surface conditions of various bodies, and its magnetic field also has widespread influence. The temperatures and pressures near the centre of the Sun are sufficiently high to sustain the nuclear reactions that result in its prodigious output of electromagnetic radiation. The planets, with their much smaller masses, cannot support such reactions. They are generally observed as a result of reflected or absorbed and re-emitted sunlight.

Before considering the properties, formation and evolution of bodies in the Solar System, we shall look at their motion and how this governs our view of celestial objects from the Earth's surface.

3.3 Orbits

Broadly speaking, the Solar System consists of objects orbiting other objects in more-or-less circular paths. The planets orbit the Sun and they, in turn, have satellites and rings in orbit around them.

- Why can the orbits of Solar System objects be described as 'well-ordered'?
- The orbits of the planets and asteroids all lie in (almost) the same plane, and they all move around the Sun in the same direction.

As you will see later in this chapter, this well-ordered motion helps astronomers to explain the origin of the orbital motion of planets and their satellites.

An understanding of orbital motion is fundamental to astronomy. It is crucial in the design of space missions and, as you will see in Chapter 6, it enables astronomers to deduce the existence of planets associated with other stars. Stars can orbit one another and they also move in orbit around the centre of a galaxy. This section introduces some key ideas about orbital motion.

People sometimes wonder what keeps the Moon in orbit and stops it crashing to the Earth. This is a perfectly reasonable question to ask. If you lift an object above the Earth's surface and let it go, it falls to the ground, pulled down by the force of gravity. Why doesn't this happen to the Moon? Indeed, why don't the Earth and other planets fall into the Sun? To answer that question, and to see the role that gravity plays in the story, first requires an examination of circular motion.

3.3.1 Circular motion

If you set an object in motion it will move in a straight line, unless there is something pushing or pulling it into a curved path. To keep an object moving in a circular path, it needs constantly to be nudged sideways – there needs to be some force (that is, a push or a pull) directed towards the centre of the circle. The technical name for a force directed towards the centre of a circle is a **centripetal force** (centripetal means 'centre-seeking'). You can demonstrate this for yourself in the next activity.

Activity 3.1 Creating circular motion

20 minutes

For this activity you will need a table-tennis ball or large marble (or a similar smooth, smallish ball), a smooth table-top or floor, and about 1 metre of string (or wool) attached to a cork or a lump of plasticine (or other object of similar size and weight that can easily be fixed to your string). The second part of the activity (whirling the cork) needs to be done somewhere well away from people or objects that might be hit by a flying cork, ideally outdoors. Do *not* use a heavy object in this part of the activity.

First, roll the table-tennis ball (without spinning it) along the smooth surface. Note that it moves in a straight line.

Next, try to make it follow a curved path (again, without spinning it). You will find that, left to itself, it always follows a straight line. To get a curved path, you need to keep nudging it sideways, as shown in Figure 3.3. If you could exert a steady force rather than a series of taps, you could make the ball move in a smooth curve because you would be supplying the necessary centripetal force.

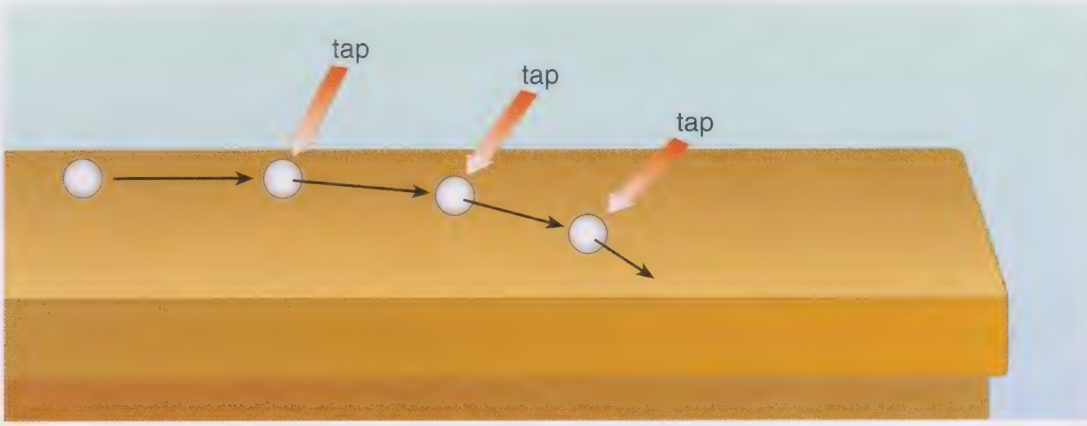


Figure 3.3 Making a table-tennis ball travel in a curve.

Figure 3.4 Letting go of a whirling object.

One way to supply a steady centripetal force is to pull on a piece of string attached to the moving object. Try whirling your cork or plasticine in a horizontal circle – you will feel that you need to keep pulling on the string as you do so.

Finally, let go of the string while whirling the cork and note the way it moves. You should be able to see that it continues to move in the direction it was heading at the time of release, as shown in Figure 3.4.

The need for a centripetal force applies to *all* cases of circular motion. In the example of the whirling cork, the force providing the inward pull is easy to see, but sometimes it is less so. For example, when a car is rounding a bend, the thrust of the engine and the grip of the tyres on the road combine to produce the necessary centripetal force. ◀

3.3.2 The Moon's orbital motion

What about the Moon? The Moon orbits the Earth in a (near) circular orbit.

- What must be providing the centripetal force for the Moon's orbit?
- The force of gravity acting between the Earth and the Moon keeps the Moon moving in its near-circular path.

- What would happen to the Moon if gravity suddenly stopped acting?
- The Moon would drift off into space since there would be nothing to hold it in orbit around the Earth.

If the Moon was simply suspended above the Earth and dropped, rather than moving in orbit, it would indeed move directly towards the Earth, pulled by gravity. In fact, it also has 'sideways' motion, and the overall effect is an orbit around the Earth. So, in wondering why the Moon does *not* fall towards the Earth, perhaps we should ask what gives it its sideways motion. Astronomers believe that the Moon formed from material ejected from the Earth in a giant impact. Some of this material would have ended up swirling around the Earth, where it gathered to form the Moon. The swirling motion is preserved in the form of the Moon's orbital motion.

So, in summary, we can explain the Moon's orbital motion. It was acquired from the swirling material from which the Moon formed, and the Moon is kept in a near-circular orbit by the force of gravity acting between it and the Earth.

3.3.3 Gravity and orbits

Having explained the Moon's orbital motion, the same principles can be extended to other orbiting bodies. First, it is important to say something about the nature of gravity. Gravity is familiar to us as the force that pulls objects towards the Earth, but our planet is not special in exerting this force. In fact, gravity acts between *all* objects.

The strength of this attractive force increases in proportion to the product of the masses of the two bodies and decreases in proportion to the square of the distance between their centres. Thus, the more massive the bodies and the closer they are, the stronger the force. Just as the Earth and the Moon are attracted towards each other by gravity, so too are all bodies. Even you and this book are attracted to one another by gravity, but the force between small objects is so weak that it is normally unnoticed. We are usually only aware of gravity when at least one object is almost planet-sized.

The mass of a star (or, more correctly, the combined mass of the star and an orbiting planet) can be calculated using the size and period of a planet's orbit, together with a knowledge of the laws of gravity. Similarly, the mass of a planet can be calculated from the orbit of a satellite (assuming the mass of the satellite is small compared with that of the planet).

The planets were all born from material that was already in a swirling orbital motion (see Section 3.7.1), so the satellites and planets created from such material also had initial orbital motion, sustained ever since by gravity.

3.4 The view from the Earth

3.4.1 Daily and annual changes

The movement of the Sun across the sky each day and the changing seasons are such a part of our daily lives that, surprisingly, many people are not aware of the reasons for these phenomena. Perhaps less surprising, in this age of light

pollution, is a lack of awareness of the apparent motion of the stars. The word 'apparent' is used here because the perceived movement of an object can actually be caused by the motion of the observer. This section examines the apparent motion of celestial objects as seen from our moving observatory, the Earth.

The Earth, in common with the other major planets, orbits the Sun and rotates on its own axis (an imaginary line joining the north and south geographic poles). During a day, the Sun, the Moon and the stars all appear to move across the sky – rising in the east, reaching their highest point when in the south (in the north if you live in the Southern Hemisphere), and setting in the west.

- What causes this apparent daily east-to-west motion?
- It is the motion of the observer on the Earth's surface rather than the motion of the Sun, the Moon and the stars. The Earth is spinning on its own axis, causing the apparent movement of all objects in the sky in the opposite direction.

You can test this for yourself either with the planetarium software on the CD-ROM or by direct observation as follows. As soon as it is dark on a cloudless night, go outside and find an observation point that you can return to later; you could mark the spot in some way. Identify a few bright stars, some in the eastern sky and some in the western sky – you might need to use a compass to find east and west. The stars need not be low down, close to the horizon but, whatever the case, note their approximate positions in the east with respect to any buildings, trees or hills in the east, and likewise for the stars in the west. If you return to your observing position at hourly intervals you will see that the stars in the east rise higher in the sky and those in the west move lower, or may set completely.

If you return to your observing position at the same time of night a few weeks later, what would you then observe? The stars in the east will be higher in the sky and the stars in the west will be lower – some might even have set. This means that, for example, if you go out at 22.00 hours, the positions of the stars will depend on the date – the stellar sky at a given time is not the same on all dates, i.e. there are seasonal changes.

- What causes the east-to-west motion of stars seen at the same time on different dates?
- Again it is caused by the motion of the observer on Earth. The Earth is orbiting the Sun, so the position of the Sun with respect to the stars (which determines the time of sunset and sunrise) changes during the year.

Now suppose that there is a bright planet in the sky, for example Mars.

- Would you expect Mars to move like the stars or in a different way?
- Mars, like the Earth, is in orbit around the Sun, so its position relative to the Sun *and* the stars also changes during the year.

Note that the stars are regarded as being 'fixed' to the sky (the concept of the sky as a sphere surrounding the Earth is known as the **celestial sphere**). In reality, stars are not all at the same distance and they are moving through space at high speed, but their distances are so great that this motion is not noticeable except over very long time-scales.

Figure 3.5 will help you understand the motions described above. It shows a plan view of short segments of the orbits of Earth and Mars as viewed from above the North Pole side of the Earth. Position 1 shows Earth and Mars at the same moment at one end of each orbit segment, and position 2 shows Earth and Mars at the other end of the segment, three weeks later. Note that the size of the Earth is greatly exaggerated. Mars's orbit is not quite in the Earth's orbital plane, but you can ignore that for now. The stars are *much* too far away to show in this diagram, but their directions can be indicated. The directions to stars A and B are shown, chosen for convenience so that they lie in or near the plane of the Earth's orbit. On the scale of Figure 3.5, these directions do not change appreciably as the Earth orbits the Sun – this is because distances to the stars are much greater than the size of the Earth's orbit. Therefore, the two direction lines to star A are parallel, and so are the direction lines to star B.

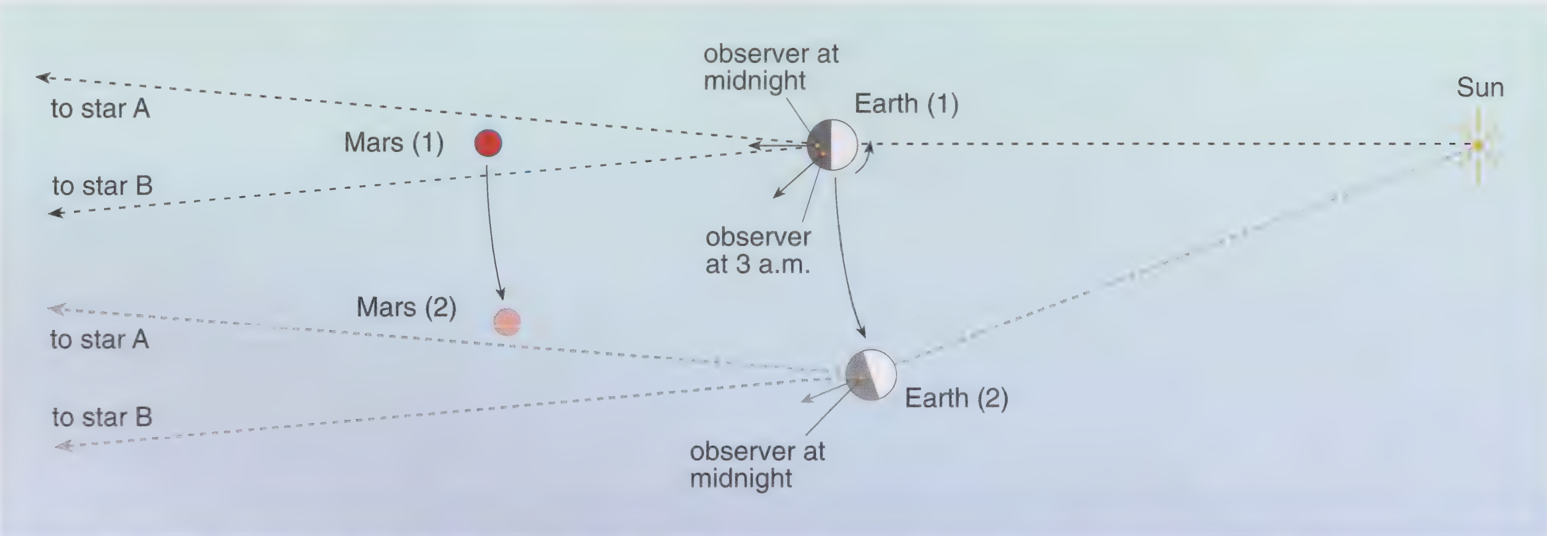


Figure 3.5 Earth, Mars and the directions to stars A and B on two different dates.

An observer is shown at the location marked. This is on the spherical surface of the Earth, at a mid-latitude in the Northern Hemisphere. The arrow pointing from the observer, directly away from the Earth, is approximately in the plane of the Earth's orbit, and is *always* in the southerly direction from the observer, as illustrated in Figure 3.6 (overleaf). Note that this figure is a different viewpoint from Figure 3.5 – if you regard Figure 3.5 as a plan view, Figure 3.6 is an elevation view, i.e. from the side. The side view shows the observer looking in a southerly direction up into the sky.

Returning to Figure 3.5, if you imagine you are the observer, looking outwards in the southerly direction, west is always to the right of the arrow and east to the left. At the observer's midnight, the arrow points in the opposite direction from the Sun. With the Earth and Mars in the positions marked 1, Mars is in the southerly direction at midnight, star A is slightly to the west of Mars, and star B is slightly to the east. The Earth rotates anticlockwise once a day. Therefore, three hours later, the Earth's rotation has carried the observer's southerly direction around to the orientation shown at 03:00 hours in Figure 3.5. Mars and

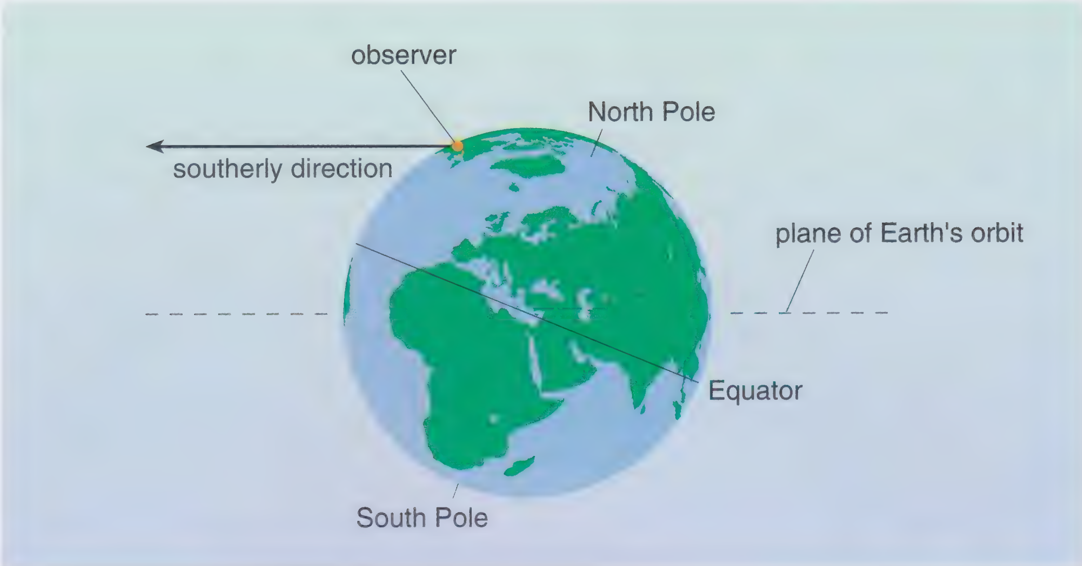


Figure 3.6 The southerly direction for the observer in Figure 3.5 (from a different viewpoint).

stars A and B are no longer in the southerly direction but in a southwesterly direction. Later they will set in the west (and earlier, well before midnight, they would have risen in the east).

Therefore, the rotation of the Earth causes the stars to rise in the east and set in the west. This applies to Mars and the other planets too. The Earth's rotation also causes the Sun to rise in the east and set in the west.

- At the observer's noon, in which direction would the arrow be pointing?
- The arrow would then point *at* the Sun, the observer and the arrow having been carried around into this alignment by the Earth's rotation.

On the day after configuration 1 in Figure 3.5, the Earth has moved only a short distance around its orbit, so the configuration is not very different. Consequently, Mars and the stars are seen in much the same directions as at the corresponding times on the preceding night. Three weeks later, however, the Earth and Mars have reached the positions marked 2. At midnight local time, Mars and the stars are now to the west of the observer's southerly direction. Moreover, the motion of Mars around its orbit has changed its position with respect to the stars. Several months later, these stars will be more or less in the same direction as the Sun, and will not be visible in the night sky.

A year later (365.3 days), the Earth is back at position 1 in Figure 3.5 but, although the stars appear to be in the same directions as before, Mars is not in the same position – its orbital period is 687 days, so it is on the far side of the Sun.

This example of Mars and the stars should explain the reasons for:

- the daily east-to-west motion of celestial objects across the sky;
- the motion of the planets against the patterns formed by the background of stars;
- the sky's changing appearance from one season to the next.

3.4.2 The seasons

You have seen that the patterns of stars that are visible at different times of year are caused by the changing relative positions of the Earth and the Sun. A far more readily observable seasonal effect (for observers at mid or high latitudes) is the change in daylight hours and consequent changes in the average daily temperature.

- Could the seasons be caused by the Earth's orbit not being circular (i.e. the Earth being further away from the Sun in winter)?
- No, for three reasons: (a) the Earth's orbit is only very slightly non-circular, so the effect of changing distance from the Sun is negligible; (b) winter occurs at the beginning of the year in the Northern Hemisphere and in the middle of the year in the Southern Hemisphere; (c) it does not explain why the hours of daylight change with the seasons.

The seasons are caused by the Earth's axis of rotation *not* being perpendicular to the plane of its orbit but being *inclined* to the perpendicular at an angle of approximately 23.5° (see Figure 3.6). The direction of the Earth's axis remains fixed with respect to the distant stars but *not* with respect to the Sun. Figure 3.7 shows how the North Pole tilts towards the Sun in the northern summer, so that the Sun reaches higher in the sky, remains above the horizon longer and provides more heat.

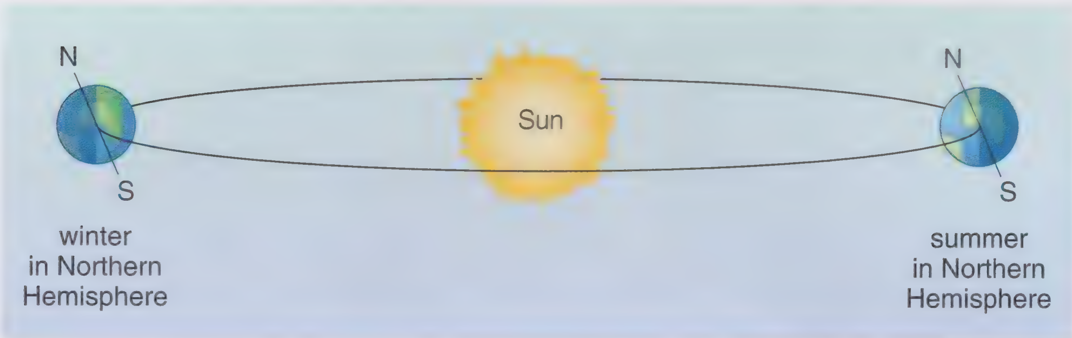


Figure 3.7 The alternating seasons as the Earth orbits the Sun (not to scale).

3.4.3 Lunar phases and eclipses

The Moon is one of the few objects in the Solar System that can be seen as anything other than a point of light by the unaided eye.

Figure 3.8 (overleaf) shows a plan view of the Moon's orbit around the Earth as seen from above the North Pole side of the Earth. Note that the Moon's orbit lies in nearly the same plane as the Earth's orbit around the Sun. On this scale the Sun is so far away that its light can be shown as sweeping across the Earth–Moon system in parallel lines. The sizes of the Earth and the Moon have been exaggerated ten times with respect to the orbit size.

When the Moon is at position 1 in its orbit, it is in roughly the same direction as the Sun. The side facing the Earth is dark so the Moon cannot be seen at all. This is the moment of the new Moon. At position 2 the Moon is half-full

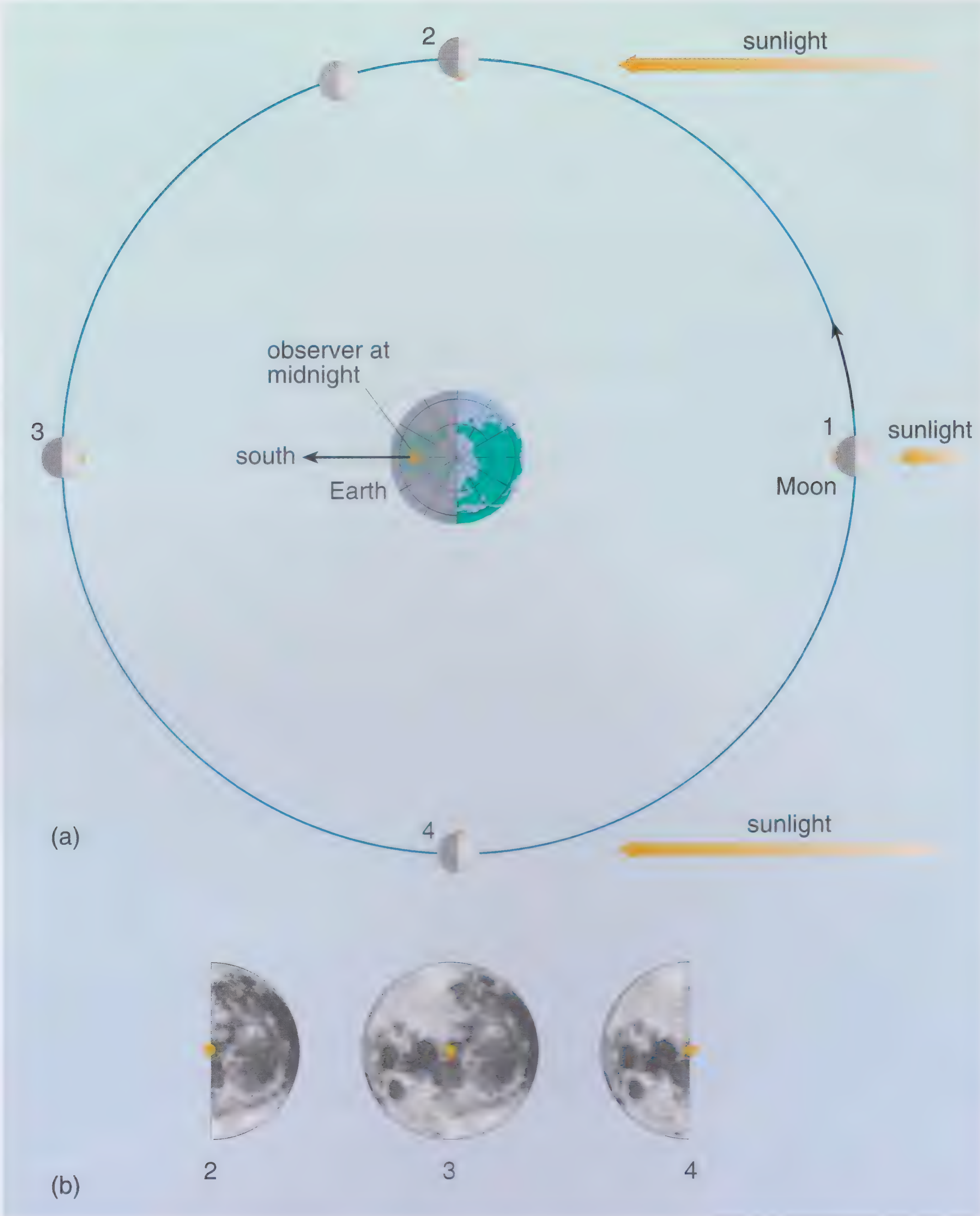


Figure 3.8 (a) The Moon in its orbit around the Earth. (b) The Moon as seen from the Earth in positions 2, 3 and 4 in (a). Note that the drawings in (b) are inverted, as happens with some astronomical telescopes.

(first quarter), at position 3 it is full, and at position 4 it is again half-full (last quarter). Each particular shape of the illuminated Moon as seen on Earth is called a **lunar phase**. The average time between successive new Moons – 29.531 days – is called the **lunar month**. With this orbital period the Moon moves appreciably around its orbit from one night to the next. For example, suppose that on a particular night the Moon is in position 2, i.e. half-full. For an observer at their midnight the Moon will be setting on the western horizon. At midnight the following night the Moon will be in the position shown left of position 2 in Figure 3.8. It will be distinctly greater than half-full and will have moved eastwards so that it is not as close to the western horizon.

The Moon rotates in just the right way for it to keep the same face to the Earth (as indicated by the yellow dots in Figure 3.8). The far side was not revealed until 1959 by the USSR spacecraft *Lunik III*.

You might think from Figure 3.8 that at every new Moon there is a **solar eclipse,** i.e. that the Moon will be seen to block the Sun from some part of the Earth's surface. This does not normally happen because the Moon's orbit is tilted by about 5° from the plane of the Earth's orbit (Figure 3.9a). The orientation of the Moon's orbit plane is not fixed with respect to the stars, the Earth or the Sun. It gradually changes with time so that it could be oriented as shown in Figure 3.9a or Figure 3.9b or anywhere in between. A solar eclipse only occurs when the Moon's orbit is orientated as in Figure 3.9b, at the same time as there is a new Moon.

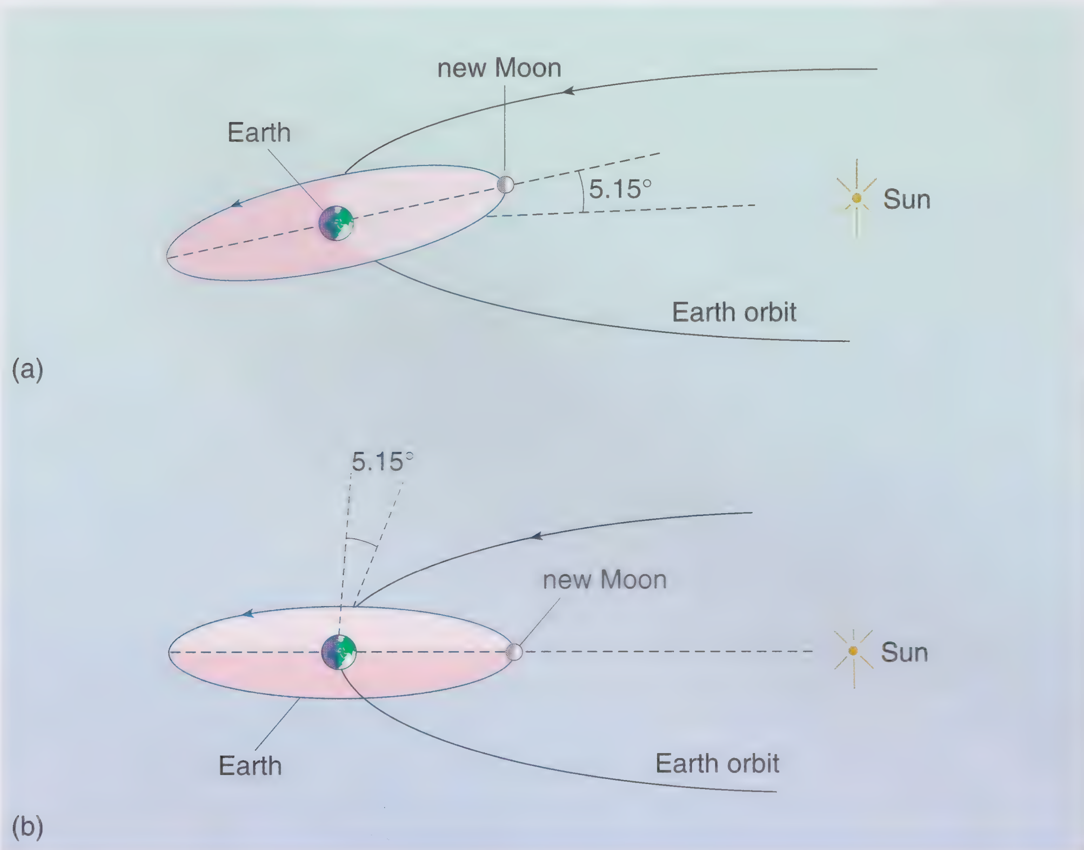


Figure 3.9 The orbit of the Moon: (a) when solar eclipses are not possible; (b) when a solar eclipse is possible if the Moon is in the new Moon position.

A solar eclipse is illustrated in more detail in Figure 3.10a (overleaf). This shows the situation at one instant. The *umbral shadow* is the name given to the shadow cast on the Earth from within which the Sun's photosphere is completely obscured. This reveals the solar corona (see Figure 2.1). The *penumbral shadow* is the name given to the shadow from within which the Sun is only partly obscured – some of the bright surface remains visible. The orbital motion of the Moon and the rotation of the Earth cause the umbral shadow to travel across the Earth, typically exceeding the speed of sound, so total eclipses are rather short lived, usually a few minutes at any given location.

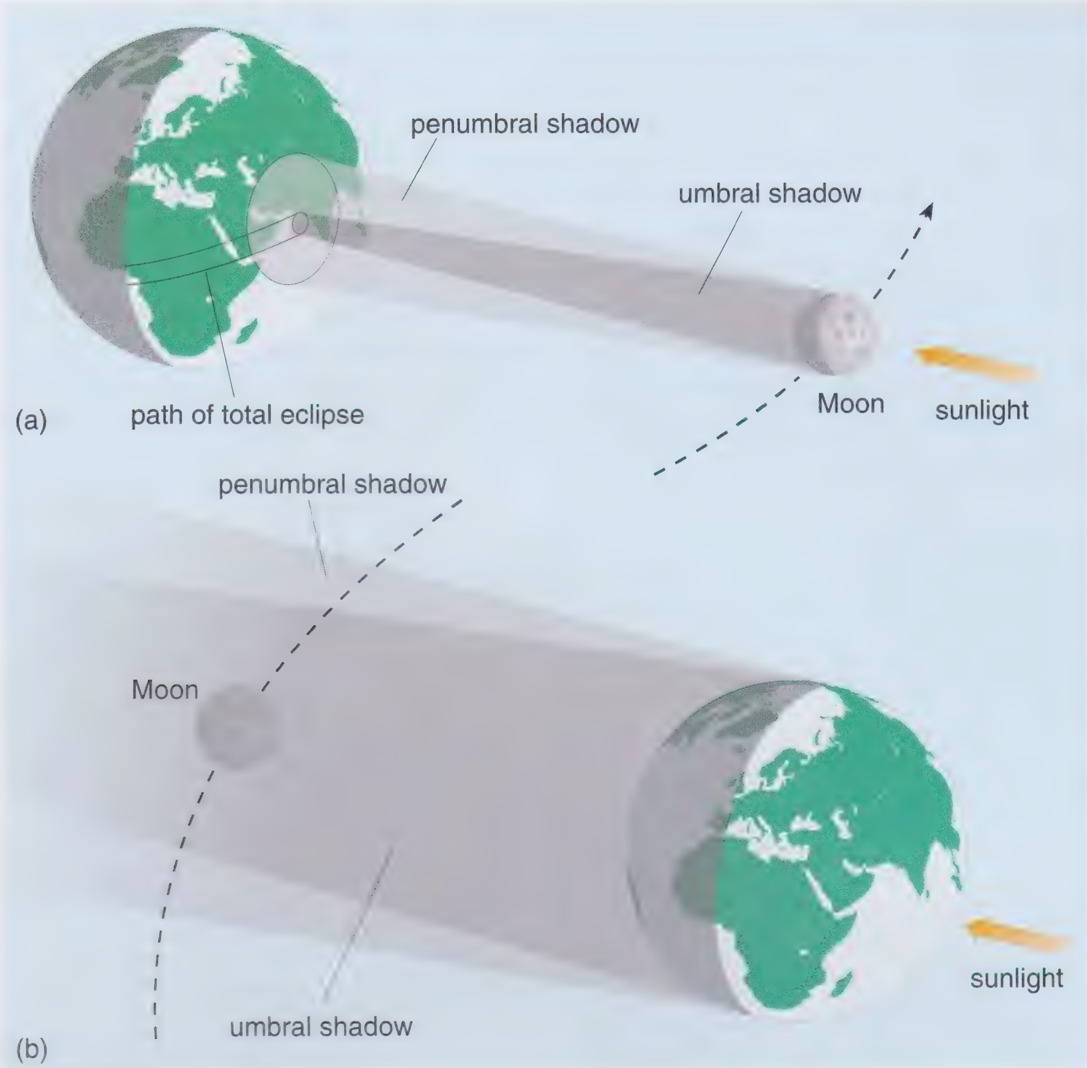


Figure 3.10 (a) A total solar eclipse. (b) A total lunar eclipse.

The Earth also casts a shadow into space and this can fall on the Moon (Figure 3.10b), resulting in a *lunar* eclipse. If the Moon is in the centre of the Earth's shadow, it becomes very dim. However, it does not disappear completely because some light is bent through the Earth's atmosphere. The light that reaches the Moon in this way has a faint coppery colour.

3.5 The planets and their major satellites

The individual planets have fascinated human beings for centuries. You have seen that, unlike the stars, which appear in fixed patterns night after night, the planets move across these patterns. Once it was established (in the fifteenth and sixteenth centuries) that the Earth and other planets all orbit the Sun, and the development of telescopes gave astronomers a more detailed view, people began to wonder about life on other planets (see Figure 3.11). With improvements in observational techniques and the advent of space exploration, we now know that intelligent life is not present elsewhere in the Solar System but microbial life could exist and is still being sought (see Chapter 6).


(a)

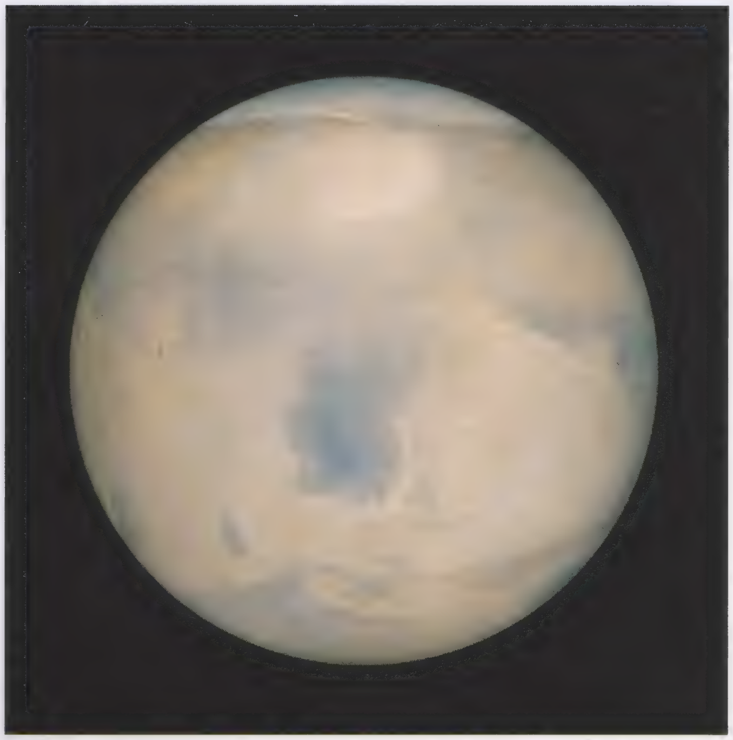

(b)

Figure 3.11 (a) The supposed channels, or 'canals', on the surface of Mars, drawn in 1905 by the American astronomer Percival Lowell, which led to speculation about intelligent life on Mars. (b) Mosaic of Mars images taken by the Mars *Global Surveyor* spacecraft. It is centred on Syrtis Major, a dark, windswept volcanic plain located on the extreme upper-left of Lowell's drawing. South is at the top in both images.

Telescopes also reveal that, just as the Earth has its Moon, some of the other planets are also orbited by smaller objects. Collectively these 'moons' are known as **satellites** – a term that has become associated with artificial objects but which originally meant natural objects.

3.5.1 Classifying planets

Our current knowledge of the planets and their satellites is based on what astronomers can observe using telescopes and on information collected by space probes. Many of these have produced spectacular images, some of which are included in the S194 Image Bank. Together with knowledge gained from studying our own planet Earth, such observations give us an understanding of conditions on other planets, and some clues about how the Solar System might have formed.

One way in which astronomers (and scientists in general) try to make sense of what they observe is to look for patterns and similarities. Astronomers have looked for ways in which planets resemble one another so they can talk about groups of planets rather than individual ones. This has helped shed some light on their history. The next activity concerns this classification process.

Activity 3.2 Classifying planets

Use the S194 Image Bank to find images of each of the major planets. Study these images and their captions. In the S194 Data Bank you will also find a table called 'Basic data on the planets', which lists the basic properties of each planet.

30 minutes

Suggest ways in which planets might be classified on the basis of this information. What characteristics do you think would lead to a helpful

classification system? Size? Colour? Presence of rings? Number of natural satellites? Some other characteristic? For each characteristic, try to think of reasons why it might, or might not, be a sensible way to classify the planets. ◀

Several of the characteristics suggested in Activity 3.2 (size, satellites and rings) lead to the same way of grouping the planets. Astronomers generally classify the planets into two main groups. The **terrestrial** (Earth-like) **planets** – Mercury, Venus, Earth and Mars – lie closest to the Sun, are fairly similar in size, and have few or no natural satellites (two at the most) and no rings. The **giant planets** (sometimes referred to as Gas Giants) – Jupiter, Saturn, Uranus and Neptune – are very much larger than the terrestrial planets, and lie much further from the Sun. Their orbits are also much more widely spaced than those of the terrestrial planets, as you saw in Table 3.1. The giant planets all have several satellites and some rings, Saturn's being by far the most prominent.

The broad similarities within the two main groups of planets do not relate just to their appearance but also to their interior structures.

3.5.2 The terrestrial planets

The terrestrial planets are made from rocky materials and have structures similar to that shown in Figure 3.12. They have dense cores mainly of iron, almost everything else being silicate rocks. The outermost layer behaves rigidly and is called the **lithosphere** (meaning 'rocky shell'). Between this layer and the core the silicate material is so hot that, even though it is not molten, it can flow at a rate of a few centimetres per year. This weak interior is stirred up by convection currents that transport heat towards the surface.

What you see when you look at a solid planetary body depends on whether there is enough heat escaping from the interior so that the lithosphere remains thin enough for it to be punctured by volcanism and deformed by the underlying

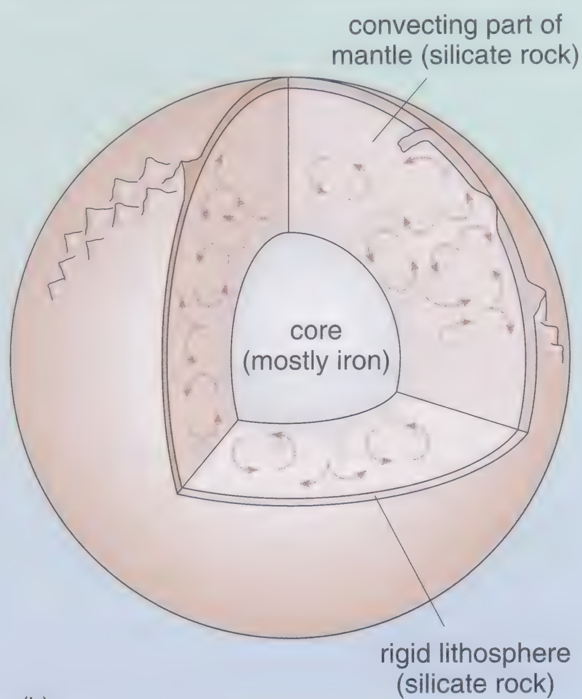


Figure 3.12 (a) Image of the planet Venus from radar data taken by the *Magellan* spacecraft in 1990. (b) Cut-away view of the interior of a terrestrial planet.

convection currents. In the case of the Earth, these processes have driven the motion of large 'plates' that make up the surface and created the continents and ocean basins and most of the mountain ranges on the Earth (such as the Alps, the Himalaya and the Andes).

Planets with lithospheres that have grown too thick for these processes to be effective show progressively less evidence of volcanism and deformation; these surface traces gradually become obliterated by craters from the occasional impact of asteroids or comets that continues even today.

3.5.3 The giant planets

Jupiter and Saturn are made largely of hydrogen and helium (Figure 3.13). This is directly visible in their atmospheres, but knowledge of how materials behave, deduced in Earth-based laboratories, leads astronomers to conclude that the atmospheres of these two planets become gradually thicker with depth. The high pressures cause hydrogen atoms to be squeezed so close together that they behave like liquid metal. The core at the centre is believed to consist largely of water and rocky materials, which are liquid at the high temperatures that occur there.

Uranus and Neptune can be thought of as resembling Jupiter and Saturn, but with less massive envelopes of hydrogen and helium, so they contain a substantially higher proportion of water and rocky materials.

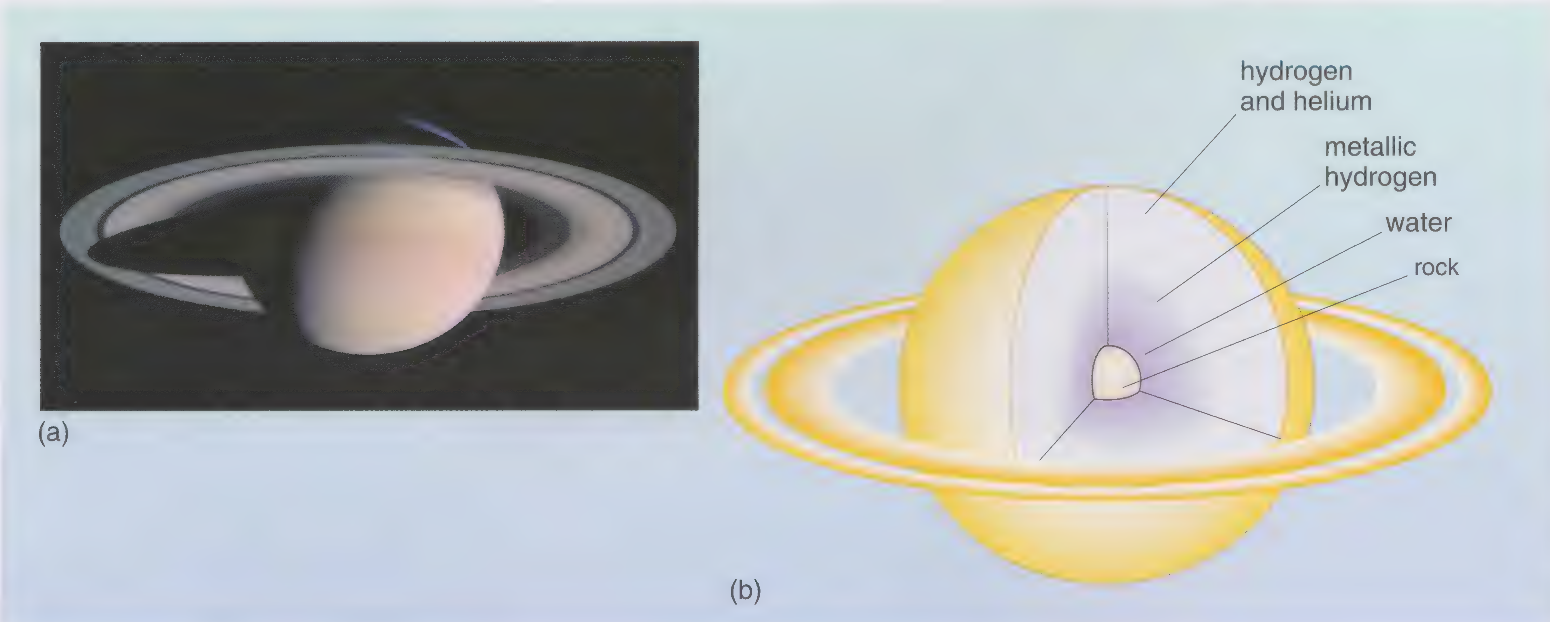


Figure 3.13 (a) Image of the planet Saturn taken by the *Cassini* spacecraft in 2004. (b) Cut-away view of the interior of Saturn.

3.5.4 Icy bodies

There are pictures of icy bodies in the S194 Image Bank, for example Europa and Triton.

- Two sorts of materials that make up planets can be broadly classified as either **icy materials** or **rocky materials**. Suggest definitions for these two terms.
- Rocky materials are solid at temperatures typical of the Earth's surface and include rocks (!), soil and metals. Rocky materials melt at high temperatures, such as occur naturally deep inside planets or are created artificially in furnaces. Icy materials are normally liquid or gas, or else they melt very

easily, at the Earth's surface. Icy materials include water (in the form of ice, liquid water or water vapour), ammonia and methane. At sufficiently low temperatures (such as those at the surfaces of planets lying far from the Sun), icy materials are solid.

An icy body can behave in a similar way to a rocky body such as a terrestrial planet. Any core is likely to be made of rocky material, but this is deeply overlaid by ice. The outermost layer of ice is so cold that it is very rigid and acts in the same way as rock on Earth, forming an icy lithosphere. Below this, provided there is a supply of internal heat, the ice becomes mobile enough to convect, leading to the same range of surface deformation and volcanism that is displayed on the terrestrial planets, except that the volcanism involves melts derived from ice rather than molten rock. In some cases there may be a reservoir of liquid water below the lithosphere. This is considered further in Chapter 6.

3.6 Minor bodies

3.6.1 Asteroids

Asteroids are rocky objects mostly orbiting in the so-called *asteroid belt* between Mars and Jupiter. The largest are several hundred kilometres in diameter but, even though over 100 000 have now been catalogued, their total mass is much less than that of a terrestrial planet. Many asteroids are believed to have altered little since their formation. Therefore, they may be examples of the material from which the terrestrial planets formed.

They are also examples of the bodies which produced many of the impact craters on the terrestrial planets and have themselves been heavily bombarded (Figure 3.14). Many asteroids have had catastrophic collisions, producing groups of fragments with similar orbits called *asteroid families*. Astronomers believe that many of these bodies consist of re-accumulated material with little internal strength called **rubble piles**.

- How would the density of a rubble pile compare with the density of the pre-impact body from which it originated?
- A rubble pile would have some empty gaps between its constituent fragments, so it would have a lower density than a solid rock of the same size.

One of the few asteroids with a measured density, Mathilde (Figure 3.14), has a density of only 1.3 g cm^{-3}, implying that it is a rubble pile with more than 50% void spaces in its interior.

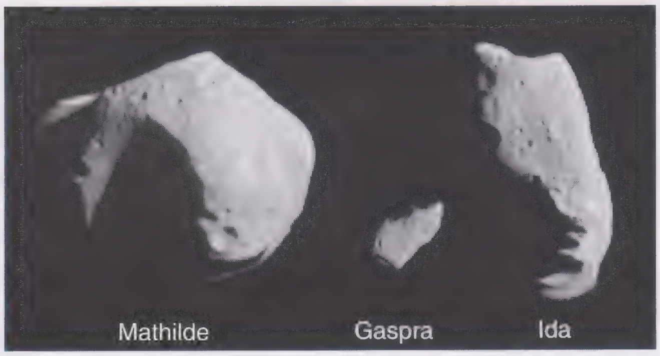


Figure 3.14 Three asteroids that have been imaged at close range by spacecraft: Mathilde, taken by the NEAR spacecraft in 1997; and Gaspra and Ida, taken by the *Galileo* spacecraft in 1991 and 1993, respectively. All three asteroids are shown at the same scale – the visible part of Mathilde is 59 km long.

3.6.2 Comets

Comets are typically a few kilometres across and consist largely of water, ice and rocky particles (e.g. Figure 3.15a). They can have extremely elongated orbits, inclined at any angle to the plane of the Solar System (see Figure 3.1). When they stray into the inner Solar System, some of the ice vaporises, dragging dust particles with it, giving rise to enormous tails and sometimes spectacular sights in the night sky (Figure 3.15b).

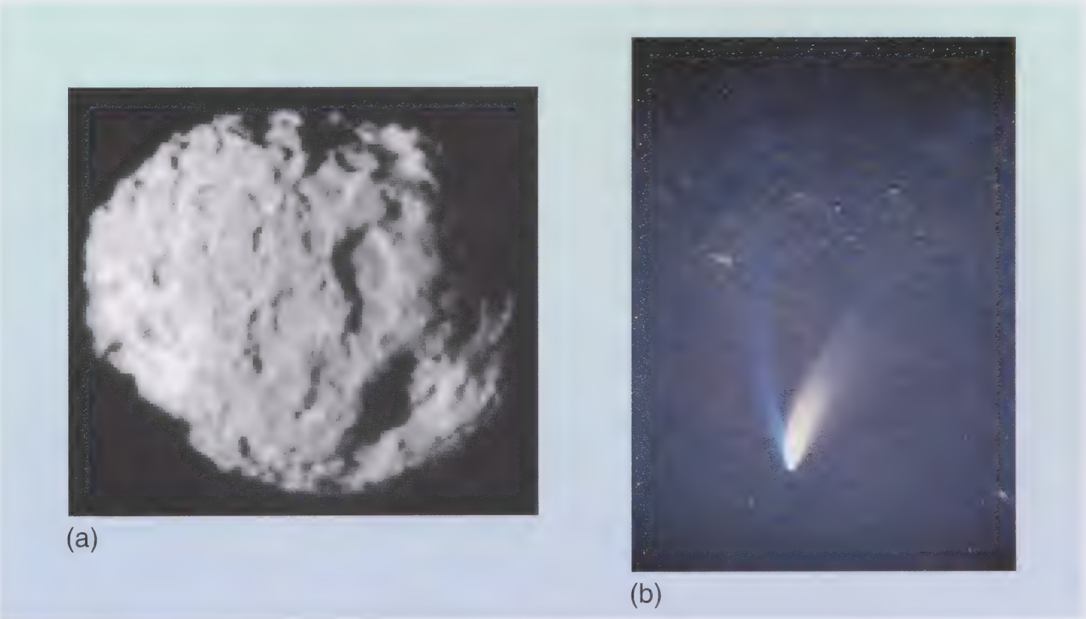


Figure 3.15 (a) The 4.5-kilometre diameter nucleus of comet Wild 2 imaged by the *Stardust* spacecraft in 2004. (b) Comet Hale–Bopp, which was visible to the unaided eye in 1997: the tenuous comet tail extends many millions of kilometres. The nucleus is far too small to be visible in this image.

The icy composition of comets suggests an origin in the outer Solar System. Most of them are currently in two regions: (i) in a spherical cloud (the **Oort cloud**) surrounding the Solar System, extending perhaps one-third of the way to the nearest star, and containing icy bodies thrown out after close encounters with the newly forming Jupiter; and (ii) trans-Neptunian objects in the outer Solar System near and beyond Neptune, centred on the plane of the Solar System. The gravitational influence of passing stars or close encounters (with each other or with the outer planets) occasionally cause such objects to enter the inner Solar System and become active.

Pluto is the one planet not discussed earlier because it is, in fact, one of the larger trans-Neptunian objects. It would not have been classified as a planet if it had been discovered recently, rather than in 1930, when a major planet was believed to exist beyond Neptune.

3.6.3 Meteors and meteorites

Extraterrestrial fragments of material entering the Earth's atmosphere are sometimes observed as 'shooting stars' when they heat up on passing through the atmosphere – more precisely, they are called **meteors**. Although meteors can be seen at any time and may come from any direction (a few per hour from a dark site), many arrive in *meteor showers*, when rates can reach as high as one per minute for a short while. There is information on meteor showers in the S194 Data Bank. Specific meteor showers occur at the same time each year, as the

Earth crosses the orbit of their parent comet and intercepts dust particles emitted by that comet during previous passages close to the Sun.

Any remnant of a meteor that survives passage through the atmosphere and reaches the Earth's surface is called a **meteorite**. Most are pieces of asteroids but a few are fragments chipped off the surface of the Moon or Mars (where the low gravity and tenuous atmosphere enable them to escape). Detailed analysis of meteorites can therefore give information about conditions in the early Solar System, and about the Moon or Mars.

- Meteors, particularly those that arrive in showers, originate from comets. Why do we not appear to have meteorites from comets?
- Comets are icy bodies that formed in the outer Solar System. The ices cannot survive the temperatures in the inner Solar System and the remaining solid particles are too fragile to survive atmospheric entry except as very fine dust (micrometeorites).

3.7 Evolution of the Solar System

3.7.1 Formation of the planets

Theories of how the Solar System formed can account for the differences in composition among the various planets – broadly speaking, the controlling factor is distance from the Sun. Although many details are still not fully understood, the Solar System appears to have formed within a rotating disc of gas and dust known as the **solar nebula** nearly 4600 million years ago.

The central part of the nebula was heated to high temperatures by the release of gravitational energy as the cloud contracted and formed the Sun. In the inner part of the nebula, where the terrestrial planets formed, the only substances to condense in large amounts were metals and silicate minerals that make up rock.

Further out, it was cold enough for water, as well as other volatile (i.e. low melting point) ices such as ammonia and methane, to condense. For this reason the planets that formed here grew so big that they were able to capture substantial amounts of the gaseous hydrogen and helium that made up most of the nebula. These became the giant planets. Some of the icy and rocky material that gathered in the vicinity of each giant planet appears to have avoided capture onto the planets themselves and went instead to form their satellites.

In the outer reaches of the solar nebula, beyond the orbit of Neptune, the planet-forming process did not progress to form a giant planet, possibly because there was not enough material in the nebula at these distances. Alternatively, current ideas suggest that the structure of the outer Solar System is the result of the gravitational influence of the giant planets migrating outwards in its early history.

3.7.2 Evolutionary processes

The appearance of bodies in the Solar System today is a result of the conditions when they formed combined with any evolutionary processes they have undergone since their formation. In many cases, these processes have

significantly changed their properties. For example, on Earth, the continual reprocessing of surface rocks through plate tectonics and erosion has mostly obliterated the record of impact craters that is seen so clearly on the Moon, Mercury and Mars. By studying different planets, we can learn more about the history of our own planet and how the whole Solar System formed and evolved.

Since the mid-twentieth century, the development of space probes has led to a tremendous expansion in our knowledge of the planets. Space missions provide close-up views of planets and their satellites, allow direct sampling of the surface or atmospheres and permit samples to be returned to Earth.

Activity 3.3 Shaping planetary surfaces

20 minutes

Many of the images in the S194 Image Bank illustrate processes that shape the solid surfaces of planets and satellites. Look through the Image Bank to find at least one image that illustrates each of the following:

- craters produced by impacts (of small bodies from space);
- active volcanoes;
- mountains produced by volcanoes;
- regions shaped by rocky lava flows;
- regions shaped by icy lava flows;
- channels or canyons produced or modified by water;
- features produced by wind action. ◀

The S194 Image Bank contains a tiny sample of the spectacular pictures from recent space missions. There are details of the missions, their experiments and the results on the NASA and ESA websites (see the S194 Data Bank for their addresses).

3.8 Chapter summary

The essential points of Chapter 3 are as follows.

1. The Earth is one of nine planets orbiting the Sun in the same direction, in nearly circular orbits, in roughly the same plane.
2. The Sun, the planets with their satellites, and a range of small bodies collectively make up the Solar System.
3. To maintain any circular motion, a centripetal (i.e. inwardly directed) force is required. The orbital motions of planets and satellites are maintained by the force of gravity.
4. The motions of the Earth, the Moon and the planets can explain the changing appearance of the night sky, the Moon's phases, the seasons and eclipses.
5. The planets in the Solar System (excluding Pluto) can be classified as either terrestrial or giant planets.
6. Asteroids (rocky) and comets (icy) are small bodies that formed in different regions of the Solar System.
7. Meteorites can provide information about asteroids and the surfaces of other planets as well as about conditions during the formation of the Solar System.

8 The Solar System is thought to have formed from a disc of gas and dust orbiting the Sun – the solar nebula. The general properties of the planets are determined by the distance from the Sun at which they formed.

9 The surfaces of planets and satellites are moulded by many processes. Space exploration has vastly increased our knowledge of the planets and their evolution.

10 Large numbers can be written in compact form using scientific notation.

3.9 End-of-chapter questions

Question 3.1 The Earth is 150 million kilometres from the Sun. Using scientific notation, what is this distance in metres? ◀

Question 3.2 Sketch the lunar phases midway between each position from 1 to 4 in Figure 3.8a. ◀

Question 3.3 In what sense does the Moon have a far side but not a dark side? ◀

Question 3.4 Why are solar eclipses rarer than lunar eclipses? ◀

Question 3.5 What are the main characteristics of the terrestrial planets that distinguish them from the giant planets? ◀

Question 3.6 Comets are described as icy–rocky bodies left over from the formation of the Solar System. Write two or three sentences saying where in the Solar System comets must have formed, explaining your reasoning. ◀

Question 3.7 In 2004, the *Rosetta* spacecraft was launched towards comet Churyumov–Gerasimenko. It will arrive in 2014, orbit the comet and deposit a lander on the surface to measure the properties and composition of the ices below the surface. Write a few sentences outlining the particular problems that might be involved in a space mission to such a small object. ◀

Question 3.8 Which features distinguish an impact crater from a volcanic crater? ◀

Observing stars

4

4.1 Sky maps

4.1.1 Star maps and atlases

Now that you know the reasons for the daily and seasonal changes in the sky (Section 3.4), we can turn to sky maps. Some newspapers and magazines publish maps each month showing the entire night sky at one particular time in the evening. However, these maps are correct only at a specific time on that date. At all other times on that date the sky looks different because of the Earth's rotation. The map may also be correct on other dates but not at the time specified, because of the Earth's orbit around the Sun. The map is also drawn for an observer at a particular latitude. In practice, these maps are adequate for an hour or so either side of the specified time, a week or two from the specified date and for an observer within 10° of the specified latitude. Clearly, it is impractical to produce maps for every other time, date and location, so a more systematic approach is required.

One solution is a star atlas, which is directly analogous to a geographical atlas. Instead of showing the surface of the spherical Earth projected on to flat pages, it shows the spherical celestial sphere projected on to flat star maps.

- If a star atlas uses the convention of north at the top of a page, why is west on the *right-hand side* of the star maps?
- West is on the left-hand side of a terrestrial map, which is seen from an apparent viewpoint above the Earth. On a star map, west is on the right-hand side because the celestial sphere is viewed from the *inside*.

While star atlases are very useful, they do not immediately show which part of the sky is visible at any given time and cannot show the positions of the Moon or the planets because they move relative to the stars. Using a star atlas to identify the part of the sky that will be visible from a given location at a given time and date is not simple. Adding the positions of the planets involves the use of *astronomical coordinates*.

4.1.2 Astronomical coordinates

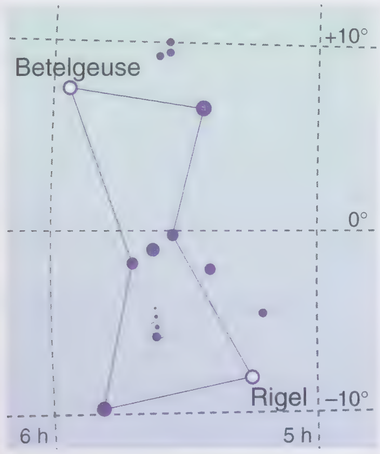
Astronomers use **celestial coordinates** to identify the positions of stars in the sky in the same way that geographical coordinates are used to locate a place on the Earth's surface. If a grid of latitude and longitude on the Earth is expanded out towards the stars and then attached to the celestial sphere, the grid becomes a celestial latitude and longitude system. Celestial latitude is called **declination** and celestial longitude is called **right ascension**. On the Earth, latitude and longitude are measured perpendicular to and around the Equator, respectively. On the celestial sphere, declination and right ascension are measured perpendicular to and around the celestial equator, respectively. The celestial equator is a projection of the Earth's Equator on to the celestial sphere and the north and south celestial poles are projections of the Earth's North and South Poles.

Declination is measured in units of degrees, 0° to 90° North (positive) or South (negative) of the celestial equator. Right ascension is measured in units of time (hours, minutes and seconds) so that 24 hours corresponds to 360° and 1 hour corresponds to 15°. This apparently strange choice of unit is due to the fact that the Earth's rotation causes a 360° rotation of the sky in 24 hours (Section 3.4.1).

Figure 4.1a shows a region of sky containing the **constellation** of Orion. The lines on the star map (Figure 4.1b) help to identify the distinctive star pattern.

The celestial coordinate system is fixed with respect to the stars, allowing their positions to be catalogued. This means celestial coordinates can be used to specify the direction of a star as seen from the Earth's surface.

(a)



(b)

Figure 4.1 (a) Photograph of the distinctive constellation of Orion. (b) Map of Orion, indicating only the brightest stars, celestial coordinates and a few objects. Rigel and Betelgeuse are blue and red supergiant stars respectively (see Chapter 5) and the Orion Nebula is a glowing interstellar gas cloud.

4.1.3 Planispheres

A **planisphere** is a device that displays a map of the entire observable night sky at any date or time for a given latitude on the Earth. It consists of two discs. On the lower disc there is a star map showing all the brighter stars that are ever visible at the latitude to which the planisphere applies, with a scale around the edge indicating dates throughout the year. The smaller upper disc has an aperture that can be rotated relative to the star map, and a scale around its edge indicating times of day. The area of sky visible in the aperture corresponds to all the dates and times that line up on the two scales as the upper disc is rotated.

Planispheres can show only relatively few stars, so they are not a substitute for a star atlas, but they are portable and allow you to easily identify which region of the sky is visible at any time.

Note that times given on a planisphere *do not* include adjustment for summer time (daylight-saving time). Thus, in the UK in summer you have to add an hour to the planisphere times to get British Summer Time.

Strictly, the times given by the planisphere are in what is called local mean solar time of the observer. For example, when the Sun is near its highest in the sky for that day, the local mean solar time is noon. However, at locations to the east, noon was earlier and to the west, it is later, i.e. it depends on longitude. In the UK it is sufficiently accurate to regard the time on the planisphere as Greenwich Mean Time at any longitude.

In the USA, it is sufficiently accurate to regard the time on the planisphere as the local zone times, e.g. Eastern Standard Time in the east. In some other countries or regions, even when daylight-saving time is *not* in force, the civil time kept there can be about an hour ahead of local solar time. This is the case in some countries in continental Europe.

Other disadvantages of the planisphere are that it can only be used by observers at the specified latitude (or within a few degrees of that latitude) and, so that it can be used in any year, the Moon and the planets are not shown.

You will find a planisphere in the course materials which can be used between latitudes 50° and 60° N. If you live outside this latitude zone, the planetarium program (see below) will perform all the functions of a planisphere and works at any location.

4.1.4 Planetarium and observatory software

The advent of inexpensive and powerful home computers has led to the introduction of software packages that combine the best features of star atlases and planispheres (and much more). The simplest type (planetarium program) allows you to replicate the operation of a planisphere or a planetarium, producing a display of the night sky at any time, on any date, from any location on the Earth. They may allow you to zoom in and produce a more detailed star map of a specific part of the sky and include the positions of the Moon and the major planets. The more sophisticated observatory software packages contain a wide range of features extending far beyond simple sky maps.

The S194 planetarium program and instructions for its use are included in the Multimedia Guide on the S194 CD-ROM.

Activity 4.1 The planisphere and the planetarium program

30 minutes

If you do this activity with both the planisphere and the planetarium program, you will see the advantages and disadvantages of each one. Remember that times and dates read from the planisphere are approximate so it may not apply precisely to your true location.

1 Find the constellation Orion (Figure 4.1). At top left you will see a star named Betelgeuse (pronounced 'betel-jers'). Find the time at which the star rises (crosses the eastern horizon) on 1 January.

2 Now simulate the passage of time during a day. Record what happens to Betelgeuse. Include the time at which it is highest in the sky and the time at which it sets.

3 Repeat this process for 1 April, 1 July and 1 October. On which of these dates is Betelgeuse *actually* visible for the longest time?

4 Find the Plough (see Figure 4.2) and record what happens to it during the course of a day. ◀

Errors and uncertainties

You may have had difficulty determining the exact time that a star sets when using your planisphere or the planetarium program for Activity 4.1. This is because of the finite size of the star image and the horizon band on the planisphere (do you place the middle or edge of the star underneath or touching the horizon?) and the irregular horizon caused by trees, etc. in the program. If you put the star in the wrong place then you will introduce an **error** into your answer. The error is the difference between your answer and the precise answer. Although your answer may have an error of a few minutes, this does not significantly affect how you did this activity or the conclusions you reached. However, in some cases, an error in a measurement may have important consequences (an example is the targeting of a spacecraft to a small body, as in Question 3.7). In general, it is not possible to determine the error in a measurement. If you could then you would know the correct answer before you started and not need to make the measurement! It is important to have a good idea of the accuracy of any quantity or measurement. A knowledge of the positions of the *Rosetta* spacecraft and its target comet to an accuracy of a few metres would be fine but, if they were only known to the nearest 100 km, the spacecraft may miss the target completely.

The **uncertainty** in a measurement or quantity is an estimate of the possible error that may be present. Using the planisphere you may measure a time for the setting of a particular star as 03:20, but not be sure whether it isn't 03:25 or 03:35. Therefore, you specify the uncertainty as 'plus or minus five minutes' and express your measurement as 03:20 ± 5 minutes.

4.1.5 Observing the sky

In the next activity you are asked to find a variety of celestial objects in the real sky. You will need a place where you can observe the night sky safely, away from bright lights and preferably not too close to tall trees or buildings – and you will need a clear night! If you have binoculars or a telescope it will enhance the activity but neither is essential. You can use your planisphere or you could prepare a star map printed from your planetarium program for the appropriate date and time.

Activity 4.2 Observing the night sky

30 minutes

For this activity you need the planisphere or star map, a torch, a notebook and a pen. It is good practice to write down notes on what you see – a written record of observations ensures that the information is not forgotten.

From your observation point, spend a few minutes looking around the night sky and letting your eyes adapt to the darkness. Try to identify some of the main

constellations, using your planisphere, set to your date and time, or a star map produced earlier from the planetarium program. What you can see depends on the time of year. The following guidelines apply to latitudes of about 40° to 60° North, which includes the UK. You will learn more about the objects you have observed in the chapters indicated below.

- The Plough and Cassiopeia (Figure 4.2) are visible all year round in the night sky, somewhere between overhead and low in the north, depending on the time and date.
- Orion (Figure 4.1) is prominent in the south in the winter and spring evening sky but is not visible in summer.
- Cygnus (Figure 4.2) is observable for most of the year but is best placed in summer and autumn.
- Pegasus and Andromeda (Figure 4.2) are visible except in spring and are best placed in autumn and winter.

Use your planisphere or the planetarium program to determine whether the Pleiades – a group of several bright stars very close together, northwest of Orion – are observable. They are best seen in autumn but are visible for much of the year. They are sometimes called the ‘Seven Sisters’. On a clear dark night, you may be able to pick out seven stars, or even more if your vision is exceptional and the sky is very dark and clear.

Note that stars are not all equally bright. They also have different colours: some are bluish-white, while others have a reddish tinge. The colours are less obvious

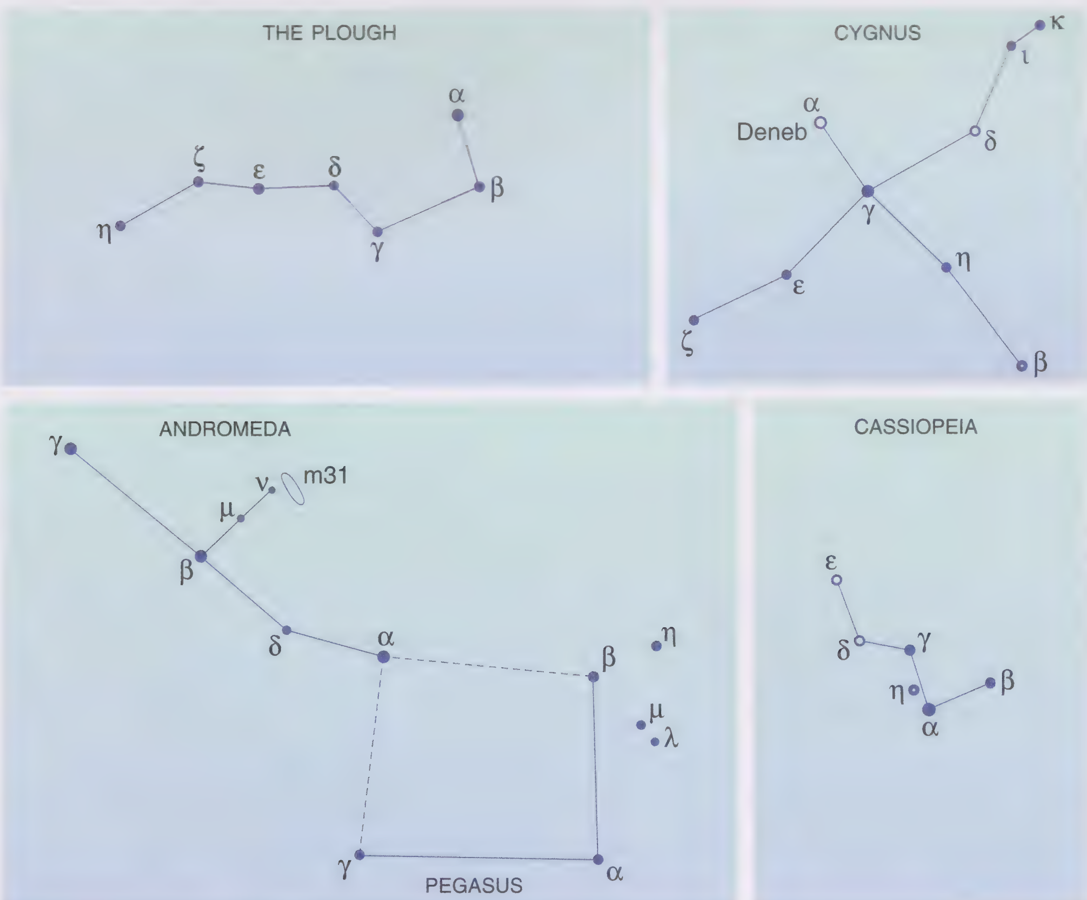


Figure 4.2 Some of the brightest constellations visible from the Northern Hemisphere.

if you are near a town where the glow of street lights spoils the view, but binoculars can help.

On a clear winter night, you may be able to see that the middle object in Orion's sword (below the three diagonal stars in Figure 4.1) is actually not a star but a **nebula** – a fuzzy patch of light rather than a sharp pin-point (Chapter 5).

Look for the Milky Way (Chapter 7), a faint milky band of light that crosses the sky through Cygnus and Cassiopeia and passes close to the red star Betelgeuse in Orion.

If Andromeda is visible and you are at a dark location, you may just be able to see a faint fuzzy object, marked 'M31' on the map. It is an easy object to see with binoculars. This is the most distant object observable with the unaided eye (see Chapter 7).

At certain times you can see the Moon and you might be able to spot some of the planets (their positions can be obtained using the planetarium software).

Figure 4.1 shows the advantage of using time-exposure with a camera because it reveals far more faint stars than you can see with the unaided eye, and it shows the colours of the stars more clearly.

4.2 Constellations and stellar distances

4.2.1 Constellations and star names

In Activity 4.2 you should have observed some constellations. These named groups of stars owe rather more to imagination than reality. Those shown in Figure 4.2, and on your planisphere and in the planetarium program, have names dating back to Ancient Greek civilisation. They are mostly named after characters in Greek mythology, whereas individual stars often have names of Arabic origin (e.g. Altair, Deneb). Eastern civilisations have tended to see the stars in smaller groups and name them differently. Constellations in the Southern Hemisphere have acquired European names relatively recently (e.g. there is one called the Microscope).

Today astronomers use constellation names only as a convenient way to refer to different parts of the sky and different stars. There is a complete list of constellations in the S194 Data Bank. Stars are named according to an internationally agreed code, in which an abbreviated form of the constellation name is preceded by a Greek letter, with α (alpha) usually being the star in the constellation that seems brightest from Earth. The remaining stars in the constellation are then named β (beta), γ (gamma), δ (delta), etc. in descending order of brightness as seen from Earth. Astronomers do not study the constellations themselves because they are not real groupings of stars, i.e. the stars in a constellation are not usually nearest neighbours in space.

4.2.2 Distances to the stars

The true nature of constellations becomes more obvious when we look at how stars are actually distributed in space. To do this, we need to find the distances to the stars. In principle at least, measuring such distances is simpler than you might think.

Chapter 1 discussed the point that other stars look much fainter than the Sun because they are so much further away. Astronomers can use this to deduce the actual distances to stars. One important observation makes this easier: namely, *stars that are the same size and colour give out the same amount of light*. So, if astronomers observe two stars of exactly the same colour, they can start by *assuming* they are the same size and, therefore, they must be giving out the same amount of light. If one looks fainter, it must be further away. By measuring the amount of light entering a telescope from each star, astronomers can work out just how much further away one star is than the other. Figure 4.3 shows this principle. Stars A and B give out the same amount of light, but B is at twice the distance of A, so its light is more spread out by the time it reaches an observer on Earth. Four times as much light from A enters the telescope (or eye), so A appears four times brighter. If B was three times the distance of A, A would appear nine times brighter, and if B was ten times the distance of A, A would appear 100 times brighter, and so on.

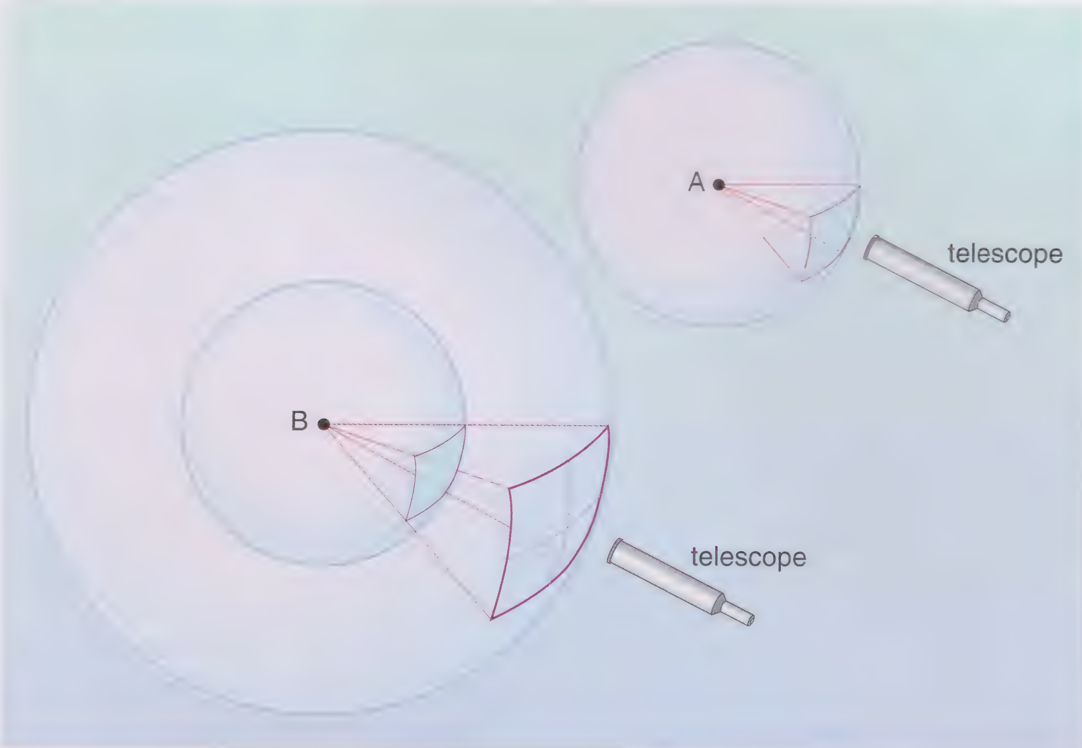


Figure 4.3 Light from a more distant star B is more spread out, so the star appears fainter than an identical star A nearby.

- If Star B is five times the distance of star A, how much brighter would A appear?
- Star A would appear 25 times brighter than star B.

Powers

When a number is multiplied by itself, the result is called the *square* of that number. For example, multiplying three by three gives nine. Nine is said to be 'the square of three' or 'three squared'. This is expressed mathematically as 3^2, which means 3×3. The *cube* of a number is that number multiplied by itself three times, so three cubed $= 3 \times 3 \times 3 = 3^3$; this can also be described as 'three to the power of three'. You should now see why, for example, $10 \times 10 \times 10 \times 10 \times 10 = 10^5$ is called 'ten to the power of five'.

- What is the general rule for describing how the apparent brightness of a star diminishes with distance?
- The general rule is that the apparent brightness diminishes with the *square* of the distance.

So, if the distance is multiplied by 2, the apparent brightness is reduced by $2^2 = 2 \times 2 = 4$. If the distance is multiplied by 5, the apparent brightness is reduced by $5^2 = 5 \times 5 = 25$, i.e. such a star has one twenty-fifth of the apparent brightness of a similar star lying at one-fifth of its distance.

Squares and cubes can also be worked out backwards, which is called 'finding the root'. Therefore, as nine is three squared, so three is the *square root* of nine, and as 27 is three cubed, so three is the *cube root* of 27.

In practice, it is not quite so easy to measure distance because some stars are the same colour but different sizes and so give out different amounts of light – but the general principle of 'faint means far' underlies many of the techniques for measuring distances.

As you might imagine from comparing their appearance with the Sun, other stars are at *very* large distances from Earth. The nearest star to the Sun, called Proxima Centauri ('proxima' is Latin for 'nearest' and the star is in the constellation of Centaurus; see Figure 4.6), is at a distance of about 4×10^{13} km; other stars are tens, hundreds or even thousands of times further away. (Note the slight change in the name of the constellation to 'Centauri' when it is put with the name of a particular star, in accordance with the rules of Latin grammar.)

When dealing with distances to stars, using kilometres leads to very large numbers which can be awkward to handle, even using scientific notation. Therefore, astronomers express large distances in terms of much larger units, such as the **light year** (abbreviated to ly). One light year (1 ly) is the distance that light (and all other types of electromagnetic radiation) travels through space in one year, which is equal to 9.46×10^{12} km (nearly ten million million kilometres). Bearing in mind that light travels extremely fast – 300 000 kilometres per second or about 660 million miles per hour – you can see why the light year is a very large distance. Proxima Centauri is about 4.2 ly from Earth.

Another unit of distance, which you might see in some astronomy books, is the **parsec** (abbreviated to pc). One parsec is 3.09×10^{13} km or 3.26 ly. Stellar and galactic astronomers prefer this unit because of the way it is defined, but there is no room to go into that here.

Note that, despite sounding like years or seconds, *a light year and a parsec are both distances NOT times*, so phrases in bad science-fiction movies such as 'That happened light years ago' or 'We'll be there in a couple of parsecs' are nonsense.

Calculations using large numbers

Many bright stars are hundreds of light years distant and the most distant object you may have seen in Activity 4.2 is over 2 million light years away. To remind you how vast the distances are, it is instructive to write them in kilometres as well, by multiplying the distance in ly by 9.46×10^{12}. To do

this on a calculator, use the button marked EE or EXP, which means 'times ten to the power of'. So, to enter 9.46×10^{12}, key in 9.46, then press EE or EXP, then key in 12. Your calculator display should resemble one of those in Figure 4.4 – different calculators display scientific notation in slightly different ways. Then you can type in the number of light years and multiply in the normal way. For example, multiplying by 228 (the distance to α Cas in ly) gives the distance in kilometres as 2.15688×10^{15} (more correctly written as 2.16×10^{15} – see the box overleaf on describing significant figures).

A common mistake is to type in 9.46×10 before pressing the EE button and typing 12. This first multiplies the number by ten, so you end up with an answer that is ten times too big.

- The distance to γ Cas (gamma Cassiopeia) is 610 ly. What is that in km?
- The answer is $(610 \times 9.46 \times 10^{12})$ km $= 5.7706 \times 10^{15}$ km, which is approximately 5.8×10^{15} km.

To get from a distance in kilometres to one in light years, divide by 9.46×10^{12}. On a calculator, enter the distance in kilometres (using the EE or EXP button as necessary), then press the '÷' button before entering 9.46×10^{12} as before.

- The distance to δ Cas (delta Cas) is 9.4×10^{14} km. What is this distance in ly?
- The calculator might display 9.9×10^{1}, i.e. the distance is 99 ly, or it might give 99 directly. (In fact, it would display many more digits but there are only two in 9.4, so only the first two digits in the answer are significant.)

Figure 4.4 Calculator displays showing the result of 9.46×10^{12}.

4.2.3 Constellations in three dimensions

As you probably saw in Activity 4.2, the five bright stars that make up the W of Cassiopeia seem quite close together in the sky. Table 4.1 (overleaf) lists these stars in decreasing order of brightness as observed from Earth and gives their approximate distances. From Table 4.1 you can see that the most distant star, γ Cas (gamma Cas), lies 11 times further away than β Cas (Caph), the closest. Figure 4.5 shows a simple three-dimensional model of these five stars. Viewed from our particular direction they appear to be quite closely grouped in a W shape, but from other directions they seem unrelated to one another – as indeed they are.

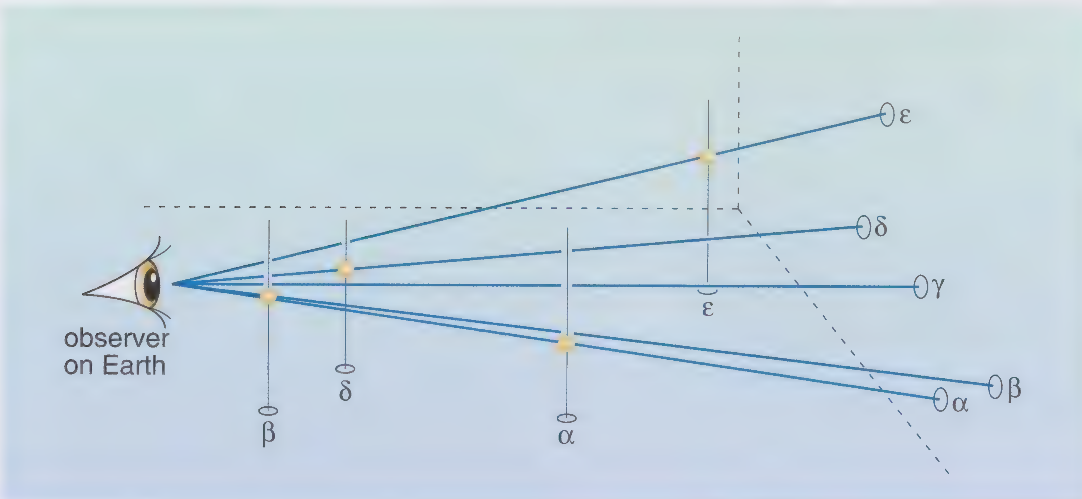


Figure 4.5 A three-dimensional view of the five brightest stars in Cassiopeia. Note that γ Cas is so far to the right that only its apparent position can be shown on this figure.

Table 4.1 The five brightest stars in Cassiopeia.

Star		
International name	Traditional name	Distance/ly
α Cas	Shedir (or Schedar)	228 ± 10
β Cas	Caph	54 ± 1
γ Cas	Cih (or Tsih)	610 ± 70
δ Cas	Ruchbah (or Rukbah)	99 ± 2
ε Cas	Segin (or Navi)	442 ± 34

Significant figures

If you are told that the mass of the Earth is 6×10^{24} kg, what does that mean? It does not necessarily mean that the mass is exactly 6×10^{24} kg, but that it lies closer to 6×10^{24} kg than it does to 5×10^{24} kg or 7×10^{24} kg. If it had been written as 6.0×10^{24} kg, you would be justified in assuming the mass is nearer to 6.0×10^{24} kg than 5.9×10^{24} kg or 6.1×10^{24} kg. A value such as 6 (or six times any power of ten) is said to be 'quoted to one significant figure', whereas 6.0 is 'quoted to two significant figures' and implies greater precision. In fact, the mass of the Earth is known to four significant figures (5.974×10^{24} kg). Expressing the mass of the Earth as either 6×10^{24} kg or 6.0×10^{24} kg or 5.97×10^{24} kg is correct to the number of significant figures quoted.

In Table 4.1, the distance to γ Cas is said to be 610 ly. The uncertainty in this distance, related to the measurements from which the distance was derived, is 70 ly. From this, the true distance is probably somewhere in the range of 540 to 680 ly (although it may be a little outside this range since the uncertainty is an estimated quantity).

- Is it reasonable to quote the distance to γ Cas as 613.573 ± 70 ly or 610 ± 68.2 ly?
- Neither way of stating the distance is correct: the first implies that the distance is known to six significant figures and therefore lies between 613.572 ly and 613.574 ly. The quoted uncertainty is inconsistent with this. In the second case, the uncertainty is quoted to too many figures. Since it is an estimate, it should be quoted to only one, or at most two, significant figures.

A common error that students make with electronic calculators is to quote the answer to a calculation to the number of figures given on the display. If you are asked to calculate how much further away γ Cas is than β Cas, your calculator will say $610 \div 54 = 11.296\,296\,3$. However, if the quoted uncertainties are a good guide, it could lie anywhere between $680 \div 53 = 12.8$ and $540 \div 55 = 9.8$! The best way to state the ratio is therefore as 'about 11': more than two significant figures implies a false level of accuracy.

4.3 The colours of stars

4.3.1 Colours and temperatures

In Figures 4.1 and 4.6 you can see that stars have different colours (you may also have detected this in Activity 4.2). These colours give astronomers useful information about the temperatures of the stars' photospheres. The next activity shows how this comes about.

Figure 4.6 A region of the Milky Way that is visible from the Southern Hemisphere. The brightest star is Alpha Centauri, a faint companion of which is the closest star to our Sun. To the right is the famous constellation of the Southern Cross (or Crux).

Activity 4.3 Getting warmer

10 minutes

For this activity, you need an electric bar (not blow) heater or a ring on an electric cooker (not the 'halogen' type). Switch it on, and hold your hand several centimetres away from the heating element. (Do not touch it!) Note what you feel as the heating element warms up and also note how its appearance changes: a darkened room will help. ◀

At first in Activity 4.3, nothing much seems to happen. Then you begin to feel heat being given out, but there is still no change in the appearance of the heating element. As you feel the element getting hotter, it begins to glow: first dull dark-red, then brighter until it eventually becomes bright orange-red and very hot. What you have experienced is an important connection between the temperature of an object and the electromagnetic radiation that it gives out (mostly visible light and infrared in this case). You can extend the example a little further. Imagine a filament light bulb; it is much hotter than a heating element and glows almost white. A low-power torch bulb is intermediate between the two – it glows yellow-white.

In principle then, astronomers can judge the temperatures of stars (and, indeed, any objects that emit light) simply by observing their colours. In practice, they split up the light into its different colours and compare the amounts of each one.

This can be done by sending light through a prism (a triangular block of glass), which splits up white light into a rainbow of colours (known as a spectrum) as shown in the continuous spectrum in Figure 1.5a.

- The star Betelgeuse, in the constellation of Orion, is orange while Rigel (also in Orion) is blue-white (Figure 4.1). Which star is hotter?
- The orange colour of Betelgeuse shows that it is fairly cool while Rigel's blue-white colour shows it is hotter.

4.3.2 Temperature and wavelength

The connection between temperature and electromagnetic radiation could be summed up as 'the hotter the brighter, the hotter the whiter'. In fact, this snappy summary is rather oversimplified because very hot objects give out more blue light than any other colour, so they appear blue rather than white. Also, *very* hot objects give out much ultraviolet radiation, and even X-rays, as well as visible light that is predominantly blue. At the other extreme, even cool objects give out some electromagnetic radiation, although it nearly all consists of infrared, radio waves and microwaves, which are invisible to human eyes but detectable by suitable instruments, as shown in Figure 4.7.

Figure 4.7 Infrared radiation detected from a shopper, red showing the warmer parts and blue the cooler parts.

A more exact summary is to say that *all* objects give out electromagnetic radiation; the hotter an object is, the more electromagnetic radiation it gives out altogether, and the more it gives out particularly at short wavelengths. As well as using words, this can be shown on a graph such as Figure 4.8. The Sun is a yellowish-white star, with a photosphere temperature of about 5500 °C. From Figure 4.8 and your observations in Activity 4.2, you can see that the Sun is a middling sort of star. Some stars are blue-white, such as Rigel, with temperatures of perhaps 15 000 °C or more, while others, such as Betelgeuse, are orange and relatively cool at only about 3000 °C.

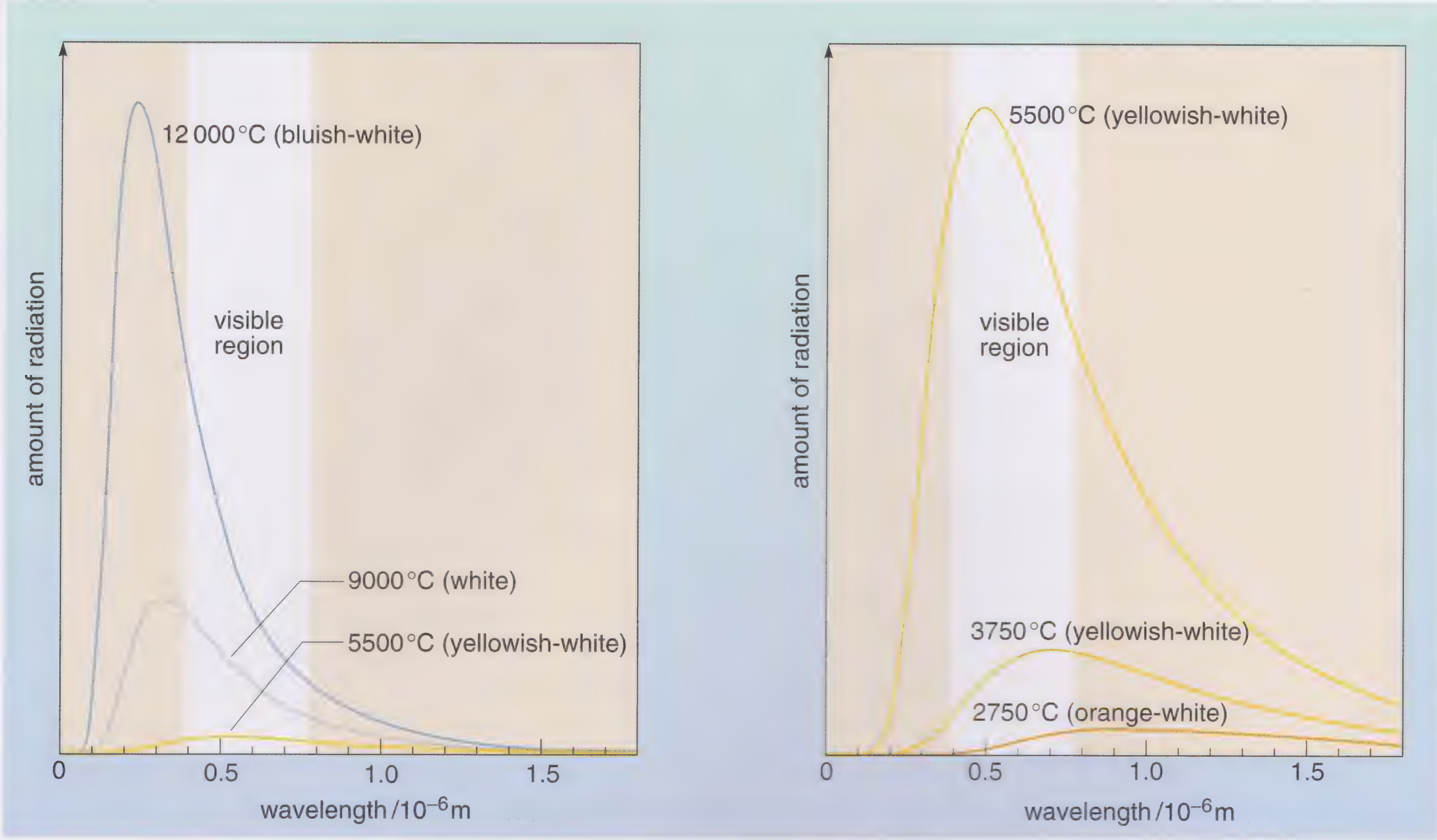


Figure 4.8 The electromagnetic radiation given out by an object at various temperatures.

You might like to refer back to Chapter 1 to refresh your memory of the types of electromagnetic radiation and their wavelength range.

- Suppose astronomers observe an object that gives out most of its radiation as X-rays. What could you say about the likely temperature of such an object?
- Since X-rays have much shorter wavelengths than visible light, they are generally given out by *very* hot objects. (For example, you saw in Chapter 2 that the Sun's corona, which gives out X-rays, has a temperature of over 1 million °C.)

Very large and very small numbers

As you saw in Chapter 1, very small numbers are needed to write the wavelengths of most types of electromagnetic radiation. As with writing very large numbers, scientific notation can be used to make the numbers more compact. Table 4.2 (overleaf) shows how very small numbers can be written by extending the pattern from Table 3.2. You may be surprised to see that $10^0 = 1$, but that follows inevitably if the pattern is continued downwards, dividing by 10 each time. For small numbers, note that the power is the same as the number of steps from the decimal point (*not* the number of zeros after the point). For example, 0.0001 is 10^{-4}, and the 1 is in the fourth place after the point. Note that the wavelengths on Figure 4.8 are given in scientific notation.

Table 4.2 Powers of ten including small numbers.

	continue up for smaller numbers	
0.0001 =	1/10000 =	10^{-4}
0.001 =	1/1000 =	10^{-3}
0.01 =	1/100 =	10^{-2}
0.1 =	1/10 =	10^{-1}
1 =	1 =	10^{0}
10 =	10 =	10^{1}
100 =	10×10 =	10^{2}
1000 =	$10 \times 10 \times 10$ =	10^{3}
10 000 =	$10 \times 10 \times 10 \times 10$ =	10^{4}
100 000 =	$10 \times 10 \times 10 \times 10 \times 10$ =	10^{5}
1 000 000 =	$10 \times 10 \times 10 \times 10 \times 10 \times 10$ =	10^{6}
	continue down for larger numbers	

Small numbers are written in scientific notation in just the same way as large numbers, i.e. with one figure before the decimal point. For example, 0.0003 is written 3×10^{-4}, and 0.0076 is written 7.6×10^{-3}. To enter such numbers on a calculator, you need to use the 'change sign' button (labelled +/–) *not* the minus button; so, to enter 7.6×10^{-3} you would type in 7.6 then press EE, then +/– and then 3.

- Visible light ranges in wavelength from about 0.000 000 4 m (violet light) to 0.000 000 7 m (red light). Write these wavelengths in scientific notation.
- The answers are 4×10^{-7} m and 7×10^{-7} m, respectively.

- On Figure 4.8 three wavelengths are labelled using scientific notation. Rewrite these wavelengths using ordinary notation.
- 0.5×10^{-6} m is 0.000 000 5 m; 1×10^{-6} m is 0.000 001 m. Also 1.5×10^{-6} m is 0.000 001 5 m (i.e. $1.5 \times 0.000\,001$ m).

4.3.3 Wavelength and composition

Sending starlight through a prism can tell us far more than just temperature. If the light is spread out finely enough, narrow dark **spectral lines** can be seen (as in Figure 4.9) where certain colours of light (certain wavelengths) are very faint or even entirely missing. This means that, if an image of a star were to be obtained at the wavelength of one of these lines, it would appear rather dim relative to images at other wavelengths. In the regions where the dark lines occur, some of the light originating from deep layers of the star is absorbed by gases in the outer parts of the star. The specific wavelengths that are absorbed

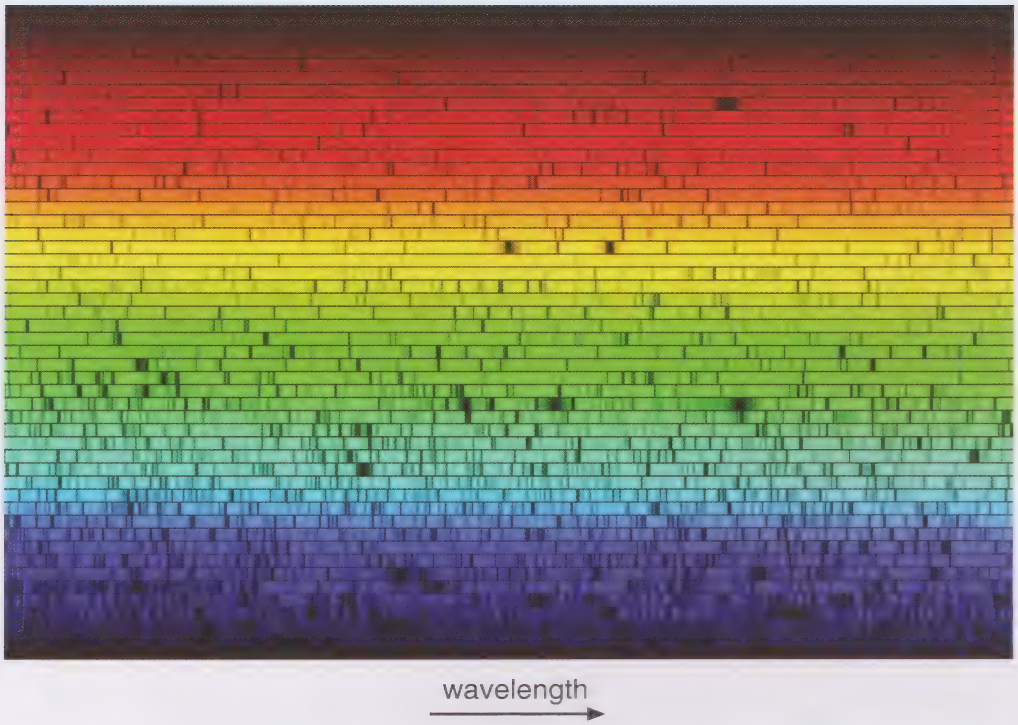


Figure 4.9 Spectrum of the star Arcturus, showing dark absorption lines due to particular atoms and molecules. The spectrum has been plotted in sections so that it fits the page with long wavelengths (red) at the top and short wavelengths (blue) at the bottom.

depend on the composition of these gases so, by studying starlight in detail, astronomers can deduce not only a star's temperature but also what it is made of. Stars are composed largely of hydrogen with small amounts of other substances. As you will see in Chapter 5, astronomers can use spectral lines in other important ways as well.

4.4 Chapter summary

The essential points of Chapter 4 are as follows.

1. The positions of stars can be specified using celestial coordinates.
2. Planispheres and planetarium software can be used to determine which stars are visible at any date and time from any given location.
3. A wide variety of celestial objects can be seen with the unaided eye.
4. Stars may be arranged in constellations, but these do not represent physical groupings of stars.
5. By comparing the apparent brightness of stars, astronomers can deduce their distances; broadly speaking, the fainter a star appears, the greater its distance.
6. The light year is the distance light travels through space in a year; stars typically lie many light years from one another and from Earth.
7. The colours of stars indicate their temperatures; blue-white stars are hottest, while reddish stars are cooler.
8. Spectral lines give information about the substances that compose a star.
9. Small numbers can be written in a compact way using scientific notation with negative numbers for the powers of ten.
10. The uncertainty in a measurement is an estimate of the error (the difference between the measured and true values).

4.5 End-of-chapter questions

Question 4.1 Orion is in the southerly sky at midnight on New Year's Day. Where will it be with respect to the Sun six months later? Draw a sketch to support your answer. ◀

Question 4.2 In the skies visible from the Southern Hemisphere, the Milky Way crosses the region of the Southern Cross. Examine Figure 4.6 and make a reasonable guess about the nature of the Milky Way. Justify your guess. ◀

Question 4.3 The four stars that make up the Southern Cross are visible in Figure 4.6. What can you deduce about the temperatures and likely distances of these four stars just by looking at this image? (On a photograph such as this, the images of brighter stars appear larger than those of faint stars. This is an artefact – the images should all be points of light.) ◀

Question 4.4 Two stars, A and B, have the same intrinsic brightness but A is four times further away from an observer on Earth than B. How will the apparent brightness of the stars compare according to the observer? ◀

Question 4.5 In Figure 1.3 the electromagnetic spectrum is labelled 0.000 001 metres and 0.000 001 *millionths* of a metre. Rewrite these numbers in scientific notation. ◀

Question 4.6 What is wrong with the following representation of distances? (i) 34.135 ± 3 ly; (ii) 29.35 ± 6.14 ly; (iii) 6 ± 0.01 ly. ◀

Star birth and death

5

5.1 Introduction

In this chapter our attention turns to star formation and evolution: how stars are made; how they change with time; and what happens when they come to an end. This is a story that astronomers have gradually pieced together. It is not easy, because stars do not form and change before our eyes – the processes involved happen far too slowly. All we have is a snapshot of many stars and nebulae at one particular time. This story is supported by much observational evidence, together with knowledge of how materials behave in Earth-based experiments, and has been developed over many years. However, it is still in the process of being refined in the light of ever more sophisticated observations.

5.2 Making stars

As you saw in Chapters 2 and 4, the Sun is a typical star. Some stars are very hot and others less hot, but all are sustained by nuclear reactions which enable them to emit vast amounts of electromagnetic radiation over millions of years.

5.2.1 Interstellar clouds – the birthplace of stars

The space between stars is not empty. It contains very thin gas and tiny specks of dust, collectively known as the **interstellar medium** (ISM). Figure 4.6 shows evidence for both gas and dust in the ISM. The dark region near the centre of the image (called the Coal Sack) is not a star-free tunnel but a cool, dense cloud; the dust contained within it obscures the stars behind. The Carina Nebula, on the extreme right, is a reddish cloud of glowing gas lit by young stars embedded within it. It is similar to the Orion Nebula that you might have seen in Activity 4.2.

Some regions of the ISM are hot and glow with visible light, while others are so cold that they can only be detected through the weak radio waves they emit; all regions are *very* much thinner than the Earth's atmosphere. Figure 5.1 (overleaf) shows part of the sky in the Orion region and the variety of gas clouds in the ISM. (Note that, with a few exceptions, the light from these regions is very faint and the details and colours seen in Figure 5.1 are only seen when long-exposure images are taken.)

To form stars, a region of the ISM has to collapse in on itself under its own gravity. The regions that do this most easily are already the densest. They are called **molecular clouds** because they contain a large proportion of gas molecules. Molecules are groups of two or more atoms, each atom being the simplest form of a chemical element, such as hydrogen or oxygen. Some molecules consist of many atoms of different elements (for more details see Section 6.2.1). The Earth's atmosphere is made up of molecular gases, mostly nitrogen and oxygen. Molecular clouds are also the coldest parts of the ISM, with temperatures of about −250 °C or even lower. They are sometimes also known as **dense clouds**, but this term is relative: they are the densest regions of the ISM but, even at their densest, they are about as thin as the very best vacuums that can be produced in laboratories! In other hotter and less dense regions of the ISM, molecules are broken up by ultraviolet light from hot stars and the gas is in much simpler forms.

Figure 5.1 Gas and dust clouds, including the famous Horsehead Nebula, in a dense part of the interstellar medium in the constellation of Orion.

Star formation can start when gas clouds collide, since that helps to squash the gas together so that parts of the cloud begin to gravitationally contract. As each part contracts, it splits into fragments, and each fragment then gravitationally contracts separately. In the same way that objects fall to Earth under gravity, the gas making up the molecular cloud speeds up as it 'falls' towards the centre of the cloud (shown schematically in Figure 5.2). In doing so, it heats up as the gas molecules collide with each other. Each contracting fragment becomes a **protostar** – the forerunner of a proper star. It takes millions of years to get from a contracting molecular cloud to a protostar because of the distances involved – a molecular cloud typically might be about 10 light years across.

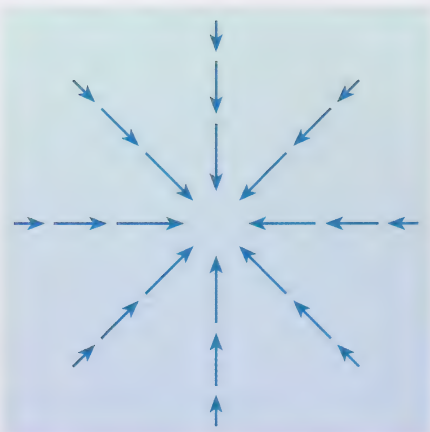


Figure 5.2 Material in a contracting cloud fragment speeds up as it falls. Each line represents the distance fallen in a given time interval.

- Protostars, like all objects, give out electromagnetic radiation. How would you expect this radiation to change as a protostar became hotter?
- The dominant wavelength range of the radiation would shift to shorter wavelengths. At first the very cool material would mainly emit radio waves, and then microwaves as it became warmer.

5.2.2 Star birth

Eventually a protostar gets hot enough to emit infrared radiation. Figure 5.3 shows infrared emission from the Orion region – an area rich in star formation. Note that this picture is colour-coded so that white means hot and red means cool.

The contraction continues and, by the time the gas has fallen through a distance of a few light years, it can reach temperatures of over 10 million degrees Celsius, i.e. 10^7 °C or more. By this time it is squashed together into a very small space – gas that was originally spread out over a few light years can be squashed into a

Figure 5.3 Infrared image of Orion covering a similar area of sky to Figure 4.1.

space similar in size to the Sun. At this point, hydrogen nuclear reactions can begin in the hottest parts (the cores) and so the protostars become stars. Their radiation heats up the surrounding ISM, which becomes hot enough to glow and then eventually disperses (see Figure 5.4 overleaf).

The idea of starting from a cold, thin molecular cloud to make hot, dense bright stars might seem a little far-fetched. What is the evidence for this scenario? One piece of evidence comes from observations where regions of the ISM containing cold molecular clouds also contain bright stars and glowing gas, which they have heated. The story is also based firmly on our understanding of how gases behave on Earth. Astronomers can use this knowledge to work out what happens to large interstellar gas clouds when they collide, and use computers to do many step-by-step calculations to show how the density and temperature change with time.

5.2.3 Multiple births

In computer models, collapsing clouds tend to break up and form *several* stars – not just one. Observations of real stars bear this out. Figure 5.4 shows a star cluster containing stars that are less than one million years old. The remaining gas and dust from the original cloud is being dissipated by the strong electromagnetic radiation from the hottest stars.

NGC 3603 is an example of an **open cluster**. These are commonly found in regions of the Milky Way where stars have recently formed and contain hundreds, or perhaps a few thousand, stars. Another type of cluster is also found in our star system – **globular clusters**. These typically contain about one million stars, are very ancient and also presumably formed from molecular clouds, although perhaps not the sort existing today.

Figure 5.4 The star cluster NGC 3603.

Open clusters are only loosely bound by gravity and disperse with time. However, many stars are born in **binary star** systems (two stars in close orbit around each other). Binary stars and even multiple stars are very common, comparable in numbers to isolated stars such as the Sun. Some binary stars are very close together so material may flow from one of the pair to the other and alter their evolution.

5.2.4 Discs and planets

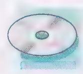
As a molecular cloud collapses, the swirling motion of the material within it results in rotation. As the cloud contracts, the rate of rotation increases, for the same reason that the spinning of an ice-skater increases as they draw their arms closer to their body. (You met this concept in Section 3.3 and will revisit it in another context in Activity 5.2.) Studies of the behaviour of collapsing gas clouds show that some of the material will spiral towards the centre like water running down a plughole, but some will remain in orbit around the central star. Figure 5.5 shows two examples of discs of orbiting dust around young stars. Planets may be forming or already exist within the discs. Our own Sun has a disc of dust of a similar size (larger than the orbit of Neptune), but it is much less dense than those seen in Figure 5.5 since much of it has been used to form trans-Neptunian objects or been ejected from the Solar System during the process.

The formation of discs around young stars suggests that planets are a natural by-product of star formation. Searches for planets, and the quest to discover whether such planets may harbour life, are discussed in Chapter 6.

Figure 5.5 Dust discs observed around young stars. The disc on the left, surrounding a 12-million-year old star, rather smaller and cooler than the Sun, is seen edge-on. The disc on the right surrounds a star very much like the Sun but only between 30 and 250 million years old.

Activity 5.1 Star formation

The S194 Image Bank contains several images of star-forming regions.



20 minutes

Find examples of the following and study their captions before answering the associated questions.

(a) Interstellar clouds: are stars likely to form in every example you found?

(b) Protostars and newly formed stars: what wavelengths of electromagnetic radiation are best for observing such objects?

(c) Open clusters: can you find examples that are associated with nebulae or contain gas clouds left over from their formation?

(d) Globular clusters: how do they differ from open clusters in their properties and location? ◀

5.3 The fate of stars

Once a star is formed, powered by nuclear reactions of hydrogen, it continues to shine steadily for many millions of years. A star fuelled by hydrogen reactions is known as a **main sequence star**. For a star such as the Sun, the main sequence stage lasts about 10^{10} years (ten billion years). Most of the stars you can see in the night sky are at this stage of their evolution and their properties (size, temperature, brightness) remain fairly constant. In the later stages of their lives, which occur relatively much more rapidly, these properties can change drastically.

The more massive the star, the more rapidly it consumes its nuclear fuel, and so the hotter its photosphere and the more brightly it glows. Eventually the hydrogen in its core is exhausted. What happens next depends on the amount of material making up the star. Here we shall concentrate on the more dramatic endpoints of the lives of stars.

5.3.1 Red giants and white dwarfs

After exhausting its hydrogen fuel supply, a middling star, such as the Sun, goes through a few more stages of nuclear reactions involving other substances. These reactions are accompanied by the outer parts of the star swelling to hundreds of times their original size, and cooling from about 6000 °C to about 3000 °C. (The reasons for this are complex and, particularly for the later stages, are still not fully understood.) The star now appears orange in colour but emits a lot of light because it is large (Figure 5.6). It is known as a **red giant**.

At the end of its life as a red giant, the star sheds much material and becomes a **white dwarf** (Figure 5.6).

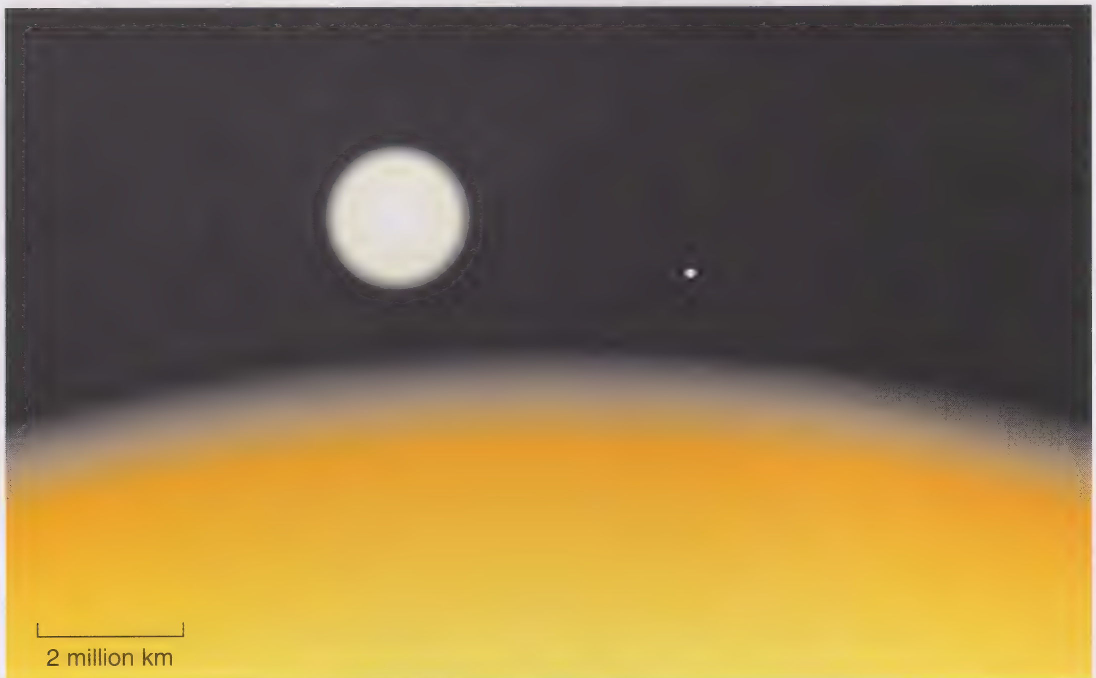


Figure 5.6 Relative sizes of stars: a star such as the Sun (top), a typical red giant (bottom) and a white dwarf (represented by the tiny white dot).

The ejected outer parts form a so-called **planetary nebula** (a confusing name, since it has nothing to do with planets). These are among the most spectacular objects in the sky. As you can see in Figure 5.7, they form shells of glowing material, each centred on a small white dwarf star. Eventually this ejected material cools and fades from view.

Betelgeuse in Orion is orange (Figure 4.1) but it is not a red giant. It is a (red) supergiant, evolved from a star about 20 times more massive than the Sun. Such stars have an even more dramatic end.

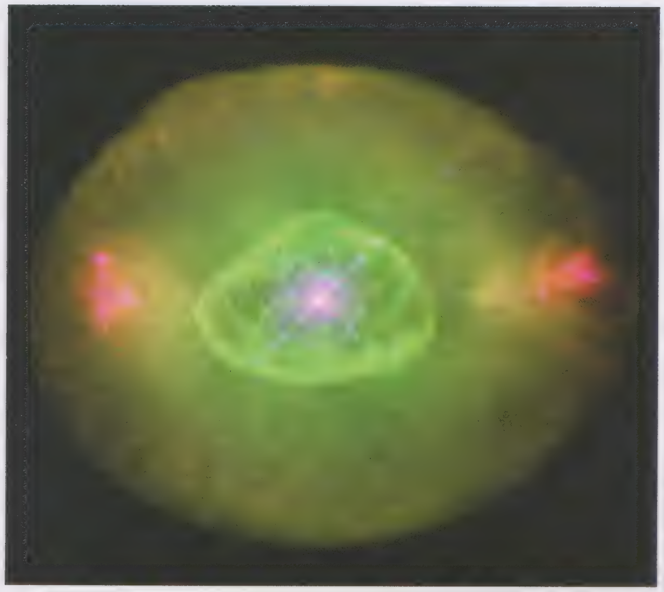


Figure 5.7 The planetary nebula NGC 6826: the hot remnant star is at the centre of the green bubble of ejected gas which represents almost half the mass of the original star.

5.3.2 Supernovae

If a star is more than about 11 times the mass of the Sun, it swells and cools, with an increase in brightness, to become a **supergiant** after exhausting its hydrogen nuclear fuel supply, and its end is much more spectacular. After going rapidly through further stages of nuclear reactions, the whole star suddenly explodes very violently, and this is called a **supernova**. This is one of the few stages in a star's life that is rapid enough for us to see it happen. Within a matter of minutes, the entire star is ripped apart, accompanied by an enormous output of light and other electromagnetic radiation. Figure 5.8 shows a picture of a supernova alongside a picture of the same part of the sky before it happened. This supernova was at a distance of about 163 000 light years but could still be seen

(a) (b)

Figure 5.8 The most recent nearby supernova which occurred in 1987. The supergiant star (the arrowed object in (a)) was transformed in about a day into a bright star visible with the unaided eye (b), which gradually faded over several months.

with the unaided eye. Figure 5.10 (overleaf) shows the Crab Nebula, the aftermath of a supernova explosion only 4000 light years away. It was so bright that it was visible with the unaided eye in daylight and was recorded in China in AD 1054.

5.3.3 Pulsars

After a supernova explosion, a small part of the original star remains at the centre. This remnant has no more nuclear fuel and continues to shrink under its own gravity. It becomes a **neutron star** – a tiny object about 20 km in diameter but with a mass greater than that of the Sun and a density 10^{17} times that of water! It may also become a **pulsar**, which is short for *pulsating radio source* (Figure 5.9). As the star shrinks, it spins more rapidly. It is said to 'pulse' because it acts rather like a lighthouse – as it rotates, its radio beam sweeps round, and a sharp flash is detected each time the beam points directly towards Earth. Activity 5.2 demonstrates these properties of pulsars.

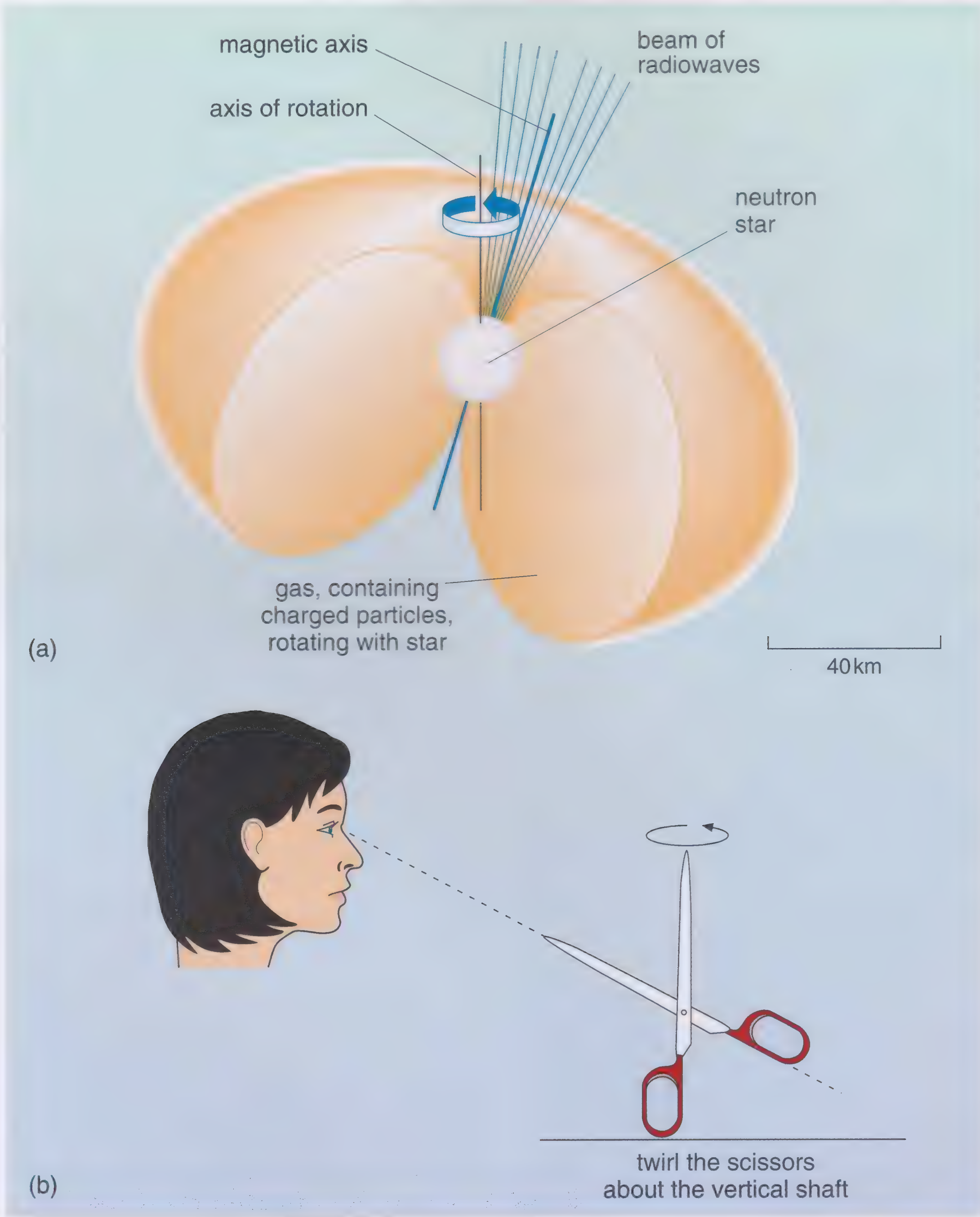


Figure 5.9 (a) An artist's impression of a pulsar. In reality, the torus (doughnut-shaped ring) of gas would extend further than shown here. (b) Modelling the way we 'see' radio pulses from a pulsar.

Activity 5.2 Modelling pulsars

10 minutes

To see what happens when a slowly rotating star collapses, you need a rotating stool or chair (e.g. an office chair). Sit with your arms and legs stretched out and spin slowly. Now bring your arms and legs close to your body – you will spin faster. An expert ice-skater can demonstrate the same effect by spinning slowly with outstretched arms, then drawing her arms close to her body to make herself spin faster. In the same way, when a rotating star becomes more compact, it spins more rapidly.

To model the 'pulsing' of a pulsar, you need a pair of scissors (preferably with straight blades and rounded ends, as shown in Figure 5.9) and some Blu-Tack® or plasticine. Use the Blu-Tack to keep the blades open and twirl the scissors about one shaft which is held upright (being careful not to stab yourself). Experiment until you find an arrangement where the slanted blade points directly at you once in each revolution. This slanted blade represents the radio beam which you can 'see' only when it is directed towards you, so you observe a series of short flashes as the pulsar rotates. ◀

5.3.4 Black holes

In some cases after a supernova, the central remaining part of the star collapses in on itself even further. Its gravity becomes so strong that nothing, not even light, can escape. This is called a **black hole**. Black holes seem to be very mysterious objects, but their existence is predicted as a straightforward consequence of the way matter is known to behave – they are not science fiction. Since light cannot escape from them, they are difficult to observe, although not, in fact, impossible. The strong gravity of a black hole draws other material towards it. This material swirls around and becomes very hot – so hot that it can emit X-rays. X-ray telescopes have detected several very compact objects that are probably black holes pulling material inwards.

5.3.5 Supernova remnants

As you can see from Figure 5.10 (overleaf), supernova explosions can leave spectacular **supernova remnants** of ejected material which continues to glow for a long time after the explosion. You can find other pictures of supernova remnants in the S194 Image Bank. Study these images and their captions carefully.

- There is a pulsar at the centre of the Crab supernova remnant but not in many other supernova remnants. Suggest three reasons for this (apparent) absence of a pulsar.

- The entire star may have been disrupted in the supernova explosion, leaving nothing at the centre; or maybe the supernova explosion left a black hole rather than a pulsar; or perhaps the pulsar's radio beam does not point towards Earth so it cannot be detected. (Another possibility is that the explosion was lopsided, propelling the pulsar out of the remnant.)

Figure 5.10 The Crab Nebula, a nearby supernova remnant.

5.4 Cosmic recycling

In this chapter you have learned about the lives of stars from their birth in dense clouds in the interstellar medium through to their often violent ends. The material ejected in a supernova explosion or a planetary nebula gradually cools and fades from view, becoming indistinguishable from the rest of the ISM. Eventually, some of it might be incorporated in a region that is cool and dense enough to contract under its own gravity, and so the process of star formation starts all over again.

Making sketches

The saying 'A picture paints a thousand words' is as true in astronomy as it is in any walk of life. The information in a picture can be further enhanced by the use of words, either in a caption or as labels indicating certain features. However, the picture may sometimes contain so much information that the point of interest may be lost in the detail. Sketches provide the solution. They can be used to highlight just the important or relevant parts of an image. Sometimes they can be used in conjunction with an image (e.g. Figure 4.1) or to replace it completely (Figure 3.4). In other cases a sketch can be used when a real image is not possible (e.g. Figure 5.9a).

When making a sketch it is important to determine which are the most important features. They may differ depending on the purpose of the sketch and may not contain the most prominent aspects of the original image. All irrelevant details should be omitted. Making good sketches does not require great artistic ability: a very simple diagram containing just the required components, clearly labelled, is far preferable, in a scientific context, to a highly embellished work of art!

Activity 5.3 The cosmic cycle

20 minutes

Figure 5.11 illustrates how matter is constantly being recycled through stars and back into the ISM.

Make a large sketch of the diagram (one of the pathways in the diagram has not been discussed and should be omitted).

Using material from this chapter and from captions in the S194 Image Bank, try to identify images that illustrate each of the labelled stages. Next to each label on your sketch, note the relevant image numbers and object names. ◀

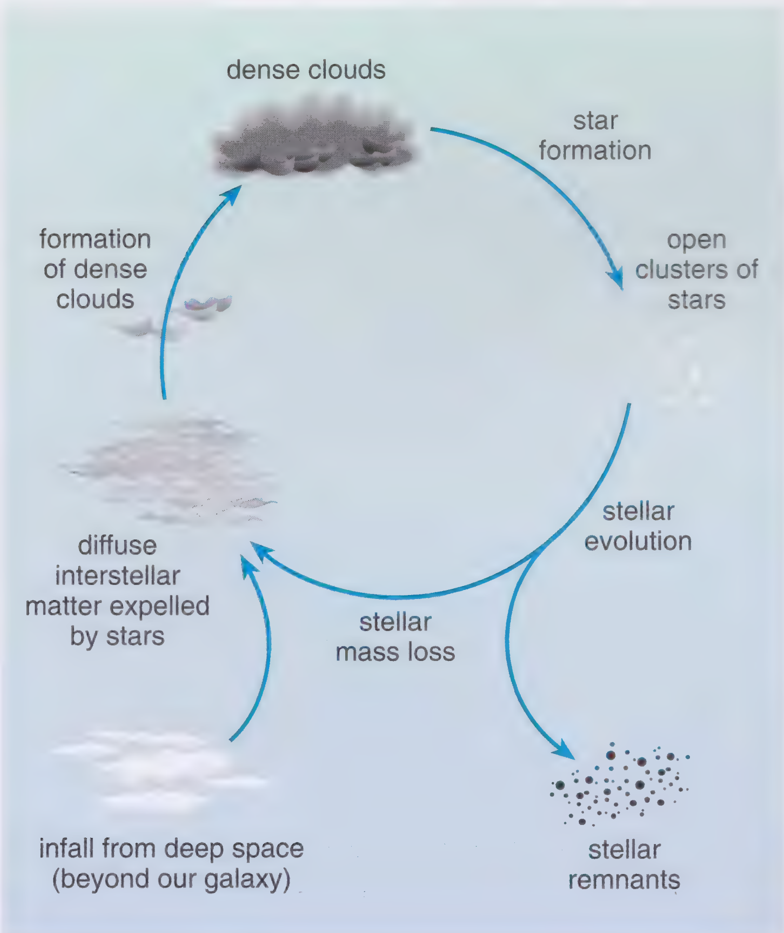


Figure 5.11 The cosmic cycle, operating between the stars and the interstellar medium.

5.5 Chapter summary

The essential points of Chapter 5 are as follows.

1 Star formation begins when a molecular cloud contracts under gravity.

2 A contracting fragment of a cloud becomes a protostar, its central temperatures increasing until they are high enough for nuclear reactions to begin.

3 A main sequence star shines steadily for billions of years while consuming its hydrogen in nuclear reactions.

4 When its hydrogen is exhausted, a main sequence star swells to become a red giant or a supergiant.

5 A red giant ejects a planetary nebula and ends as a white dwarf.

6 A star that begins with over 11 times the Sun's mass ends in a violent supernova explosion, leaving an extended remnant and possibly either a pulsar or a black hole.

7 Material ejected from stars eventually cools and may enter further cycles of star formation.

5.6 End-of-chapter questions

Question 5.1 List the following terms in the correct order to describe the life history of a star similar to the Sun: main sequence star; white dwarf; planetary nebula; protostar; dense cloud; red giant. ◀

Question 5.2 In this chapter you met various types of nebula. Find images of the Trifid Nebula, the Cat's Eye Nebula and the Crab Nebula (also shown in Figure 5.10). For each one write a sentence or two describing it and saying how it illustrates part of the life history of a star. ◀

Is there life beyond the Earth?

6

6.1 Introduction

Some scientific questions are of immediate and widespread interest, and they stir our imaginations. One of these questions is the subject of this chapter – is there life beyond the Earth? This question has surely been pondered ever since people in antiquity realised that there might be celestial bodies of rock and water beyond the Earth, but it is only in the last 50 years or so that we have made significant scientific progress towards answering it. Today, the question is still unanswered, but it is the focus of intense scientific activity. This is a fast-moving area, where much is still uncertain, but significant developments are expected in the next decade or two with space missions continuing the exploration of likely habitats in our Solar System and the search for Earth-like planets beyond it.

A few people believe that we already *know* that there is life beyond the Earth; they claim that we have been visited by aliens. Although it is easy to laugh at the notion of alien visitation, it is in fact perfectly serious to ask whether it has happened, either recently or in the past. The perfectly serious answer is that there is no scientific evidence for it. The claims lack objective facts. Certainly, there are unexplained happenings, but the important word is 'unexplained', and a belief that alien visitation is the explanation is just that, a *belief*. It is always possible that tomorrow there will be a clear and obvious visitation, but many scientists believe that *intelligent* life in the Universe is rare and the difficulty of travel over the vast distances between stars makes this possibility vanishingly small.

The Earth is the one place in the whole Universe where we *know* there is life. In searching for life elsewhere we must be guided by the key features of life on Earth, and the essential conditions for life here. Therefore, Section 6.2 starts with a quick look at life on our own planet. Then, in Section 6.3, we identify other bodies in the Solar System that might have been suitable for the emergence of life, or that might be suitable for supporting life today, and we ask whether life has already been found on any of them. In Section 6.4 we look beyond the Solar System, and consider how we might detect life on planets around other stars.

6.2 Life on Earth

Life on Earth today displays bewildering variety, yet all organisms in a fundamental sense are rather similar. The most familiar organisms are large ones – from elephants, blue whales and trees, down to spiders and fleas. Yet even at the small end of this size range an organism consists of a large number of what are called cells – about 10^6 in the case of a flea. Other organisms consist of just a single cell – bacteria are a widespread example. There is a huge variety of bacteria. Although bacteria are commonly associated with disease, most of them are harmless and many have vital roles in the health of the biosphere, such as recycling important nutrients for life. They account for a large proportion of all single-celled organisms, and such organisms accounted for *all* life on Earth from its origin nearly 3900 million years ago until as recently as about 700 million years ago – multi-celled organisms are a comparatively recent development.

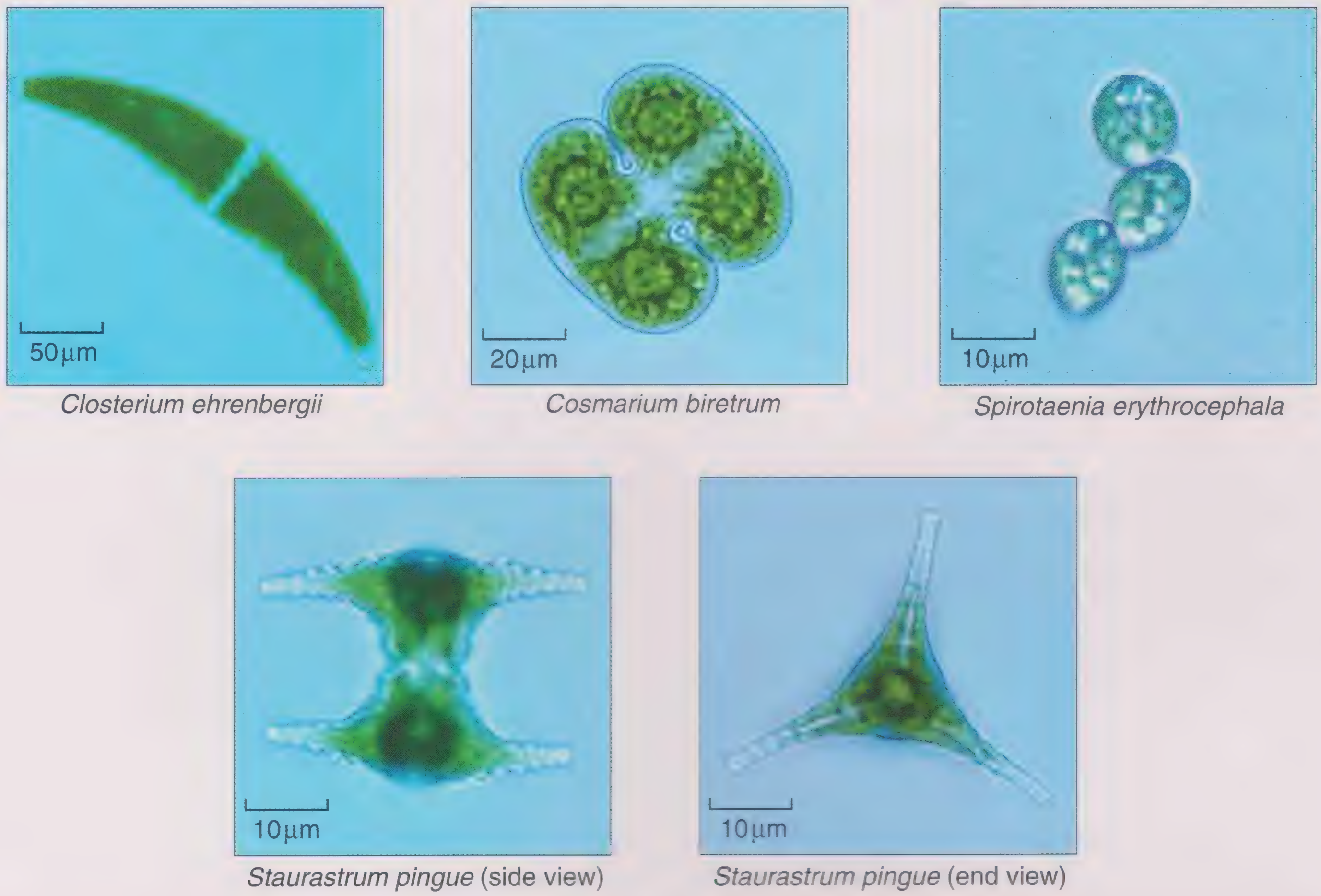


Figure 6.1 A variety of single-cell organisms. In the case at top right there is a colony of three single cells.

A few single-cell organisms are shown in Figure 6.1, where each cell is roughly a few hundredths of a millimetre across. A cell consists of a membrane that encloses liquid water that contains some other substances essential for the cell to grow and reproduce. It is these substances in the cell that define the similarity between all organisms; substances that are common to all life on Earth, and that are essential for all life on Earth.

6.2.1 Chemical elements and compounds

The substances of interest are chemical compounds. To understand what is meant by a chemical compound you need to understand what is meant by a chemical element. For our purposes, an **atom** can be regarded as the smallest building block of a molecule, where a molecule is the smallest unit of a substance (you learned about molecules in Section 5.2.1).

As you learned in Chapter 1, atoms contain a central nucleus consisting of protons and neutrons, together with orbiting electrons. Atoms are very small, about 10^{-10} m across. A **chemical element** consists of a single type of atom with a particular number of protons in its nucleus. Over 100 chemical elements are known, many of them being familiar in the everyday world, for example: hydrogen (H), helium (He), nitrogen (N), oxygen (O), neon (Ne), aluminium (Al), iron (Fe), silver (Ag), gold (Au), lead (Pb) and uranium (U). These elements are denoted by the symbols in brackets; the less obvious ones relate

mainly to the Latin name of the element, e.g. Fe comes from 'ferrum', meaning 'iron'. These letters are also used to denote a single atom of the element.

In an element the smallest unit might be a single atom. This is the case in neon, for example. Thus a sample of neon consists of a collection of single atoms of neon. The smallest unit might also be small numbers of atoms bound together. Thus, in the oxygen in the air we breathe the smallest unit is two atoms of oxygen bound together. This is written as O_2. Thus a sample of oxygen consists of a collection of pairs of oxygen atoms. (Note that oxygen can exist as single atoms under certain conditions, but its preferred state is as molecules of two atoms.)

In a **chemical compound** the smallest unit always contains more than one type of atom. For example, the smallest unit of water consists of two atoms of hydrogen and one atom of oxygen bound together (Figure 1.4). A sample of water then consists of several of these units.

- Guess how the single unit of water is denoted in terms of the symbols H and O.
- The unit of water is written as H_2O. In fact, OH_2 makes as much sense, but convention dictates otherwise.

6.2.2 The chemical compounds of life, and the search for life elsewhere

If you looked into a cell, at the fundamental chemicals of life, you would find that all life on Earth is based on huge molecules that are complex compounds of the chemical element carbon (C). Carbon can form chemical bonds with many other atoms, allowing a great deal of chemical diversity. It can also form compounds that readily dissolve in water, which is, as you will see, also essential for life. You will have heard of proteins and of DNA, and perhaps of RNA too. These are all large, complex carbon compounds containing very many atoms per molecule, and they are all essential for the processes of all life on Earth. For example, DNA contains the information for making a new generation of organisms. It comes as no surprise to chemists that carbon is the basis of life – no other chemical element comes anywhere near carbon in its ability to form the large and complex compounds that are necessary for life.

So, we should restrict our search for potential habitats for life beyond the Earth to places where huge, complex compounds of carbon can exist. The availability of carbon is no problem – it is a fairly common and widespread element. What really narrows the search is that *huge* carbon compounds can exist only under certain temperature conditions.

- Make an 'educated guess' about what might happen to *huge* carbon compounds at sufficiently high temperatures.
- They will break up.

Specifically, the huge carbon compounds that are the basis of life break up above about 150 °C, so we must confine our attention to places colder than this.

All life on Earth has some other requirements, but there is one more requirement that will be of great importance in aiding our search for life elsewhere. It is a chemical compound found in all cells, and it was referred to near the start of this section.

- What substance does all life on Earth require?
- All life on Earth, during at least some part of its life cycle, needs water.

What's more, the need is for *liquid* water. Living systems need a medium in which molecules can dissolve and readily interact to allow chemical reactions to take place. Although there are some single-cell organisms that can live in snow, they still rely on melted snow to grow. We must therefore identify places where water exists, and where the temperature and pressure are such that the water is liquid.

- At sea-level on the Earth, over what range of temperatures is water liquid?
- Water is liquid between 0 °C and 100 °C at sea-level. Thus, if the temperature is lowered to 0 °C water freezes, and if it is raised to 100 °C it turns into vapour (gas) very rapidly, i.e. it boils.

These boiling and freezing temperatures depend on atmospheric pressure. At sea-level on the Earth the average pressure is about 1000 millibars, the millibar being a unit of pressure that you might have seen on weather maps. At 1000 millibars the boiling temperature of water is 100 °C. On a mountain only 1000 metres high, the average pressure is reduced to about 900 millibars and the boiling temperature is consequently reduced to 97 °C. The boiling temperature is raised above 100 °C in a pressurised container. The freezing temperature is much less sensitive to pressure – for practical purposes we can regard the freezing temperature as 0 °C.

As the pressure is lowered below 900 millibars, the boiling temperature of water continues to fall, and approaches 0 °C at a pressure of 6.1 millibars. Consequently, below 6.1 millibars, water cannot exist as a liquid, but only as a solid (ice) or a gas. For practical purposes, assume that if liquid water can exist, complex carbon compounds can too.

To summarise: life on Earth can be described as carbon–liquid-water life and, therefore, when looking for life beyond the Earth, attention should focus on places where complex carbon compounds and liquid water could exist – conditions for the possible existence of liquid water being sufficient in practice. Then we need to see whether, in fact, these substances *do* exist, and whether life has emerged.

6.3 Potential habitats in the Solar System

In the search for carbon–water life, the type of potential extraterrestrial habitat that attracts almost exclusive attention is the surface regions of planets and their satellites, rather than interstellar clouds (such as the Coal Sack in Figure 4.6, described in Section 5.2.1) and the surfaces of stars. In the case of stars, the high temperatures make them totally unsuitable for life. The reason for ignoring interstellar clouds is less obvious. It is because they are of such low density that it would be difficult to bring together enough atoms to build up huge carbon compounds in any quantity (although quite large molecules do appear to form), and because the pressures are far too low for liquid water.

Potential extraterrestrial habitats can be divided into two categories:

1 the planets and satellites in our Solar System;

2 the planets and satellites in the planetary systems of other stars.

Activity 6.1 Where in the Solar System might we find life?

20 minutes

On the basis of the information given in the table 'Planetary data' (in the S194 Data Bank), make a list of each of the eight planets (not including the Earth) and state, with reasons, whether each one is likely to be a potential extraterrestrial habitat. In some cases you might have to decide that there is insufficient information to form any sort of judgement. ◀

From Activity 6.1 it is clear that, among the planets today, none (except the Earth) is very promising as a potential habitat. This is borne out by further data on the planets. Only one planet has any realistic chance of being a potential habitat, and that is Mars. Among the planetary satellites there are further candidates: the large satellites of Jupiter – Ganymede, Callisto and, in particular, Europa.

6.3.1 Mars

Mars is the next planet out from the Sun after the Earth. It is a rocky body, 3390 km in radius (about half that of the Earth), with a thin atmosphere of carbon dioxide, and surface temperatures that can reach 20 °C on a very good day. The average surface pressure, however, is close to the 6.1 millibar minimum for liquid water. Therefore, only in the very deepest chasms on Mars, where the pressure would be slightly higher, and even there only on the warmer days, could liquid water persist at the surface. However, the polar caps (Figure 3.11b), which are visible even in small telescopes from the Earth grow and shrink with the seasons, indicating the presence of frozen water as well as carbon dioxide. This has been confirmed by spacecraft.

Water-carved features were first seen in images of Mars acquired by the orbiting spacecraft *Mariner 9* as long ago as 1971, providing firm evidence of flowing water early in Mars's history (2 to 4 billion years ago: Figure 6.2). Subsequent

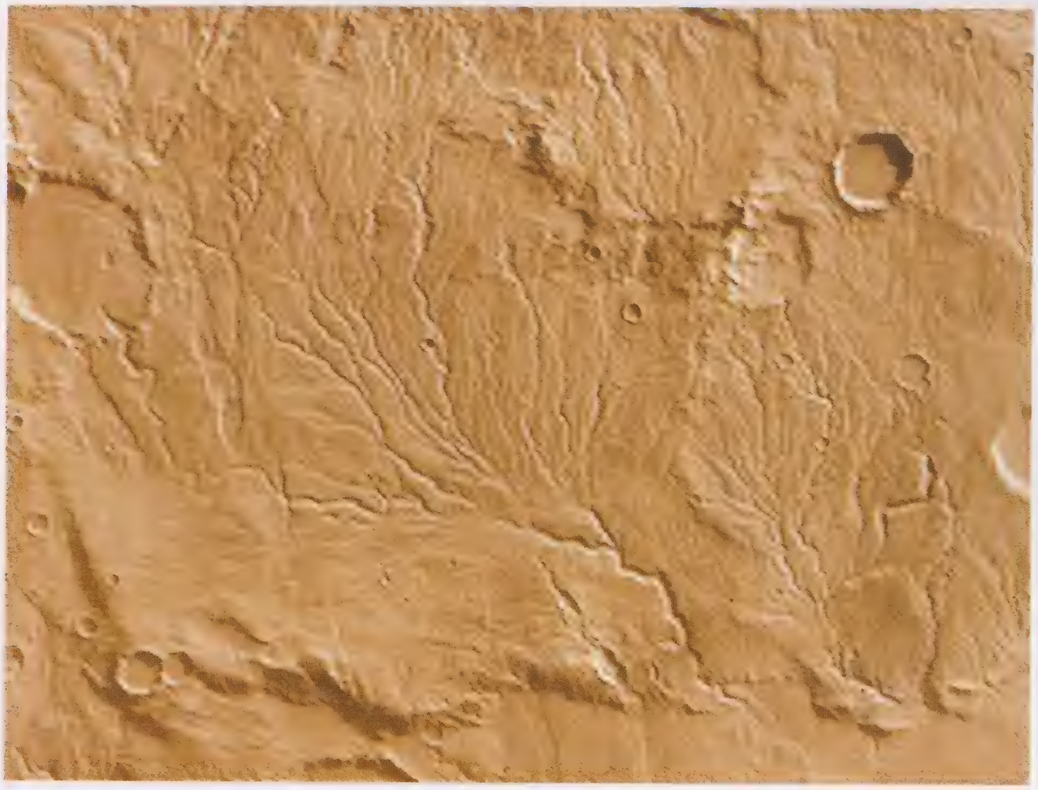


Figure 6.2 Ancient river valleys and impact craters on Mars.

Mars missions have revealed abundant evidence for the flow of water much more recently. Minerals that indicate that surface rocks were once soaked in liquid water have been detected from orbit and by landers on the surface of Mars. Figure 6.3 shows gullies that are believed to have been formed by liquid water flows less than one million years ago. Unlike similar features on the Earth, these could not have been produced by rainfall but by water released from subsurface deposits, probably as the pressure of liquid water rose and burst through a permafrost layer. Although liquid water cannot survive at the surface, water ice has been found in abundance just below the surface at high latitudes and, in some cases on the surface itself (Figure 6.4). Even at the equator there is evidence of ice lying just below the surface (Figure 6.5).

Despite the presence of water ice at or near the surface and recent water flow, there is certainly no evidence for life at the Martian surface. No tracts of vegetation have been seen from space, and the spacecraft that have landed have not seen life-forms stalking the landscape. More significantly, the landers have seen a total absence of the processes and chemical products of current life in the Martian sands. Although very little of the Martian surface has been explored in this way, it seems unlikely that there is any life at the surface today.

If there is any current life on Mars then it must be below the surface and is most likely to be deep under the surface, where the pressures are high and where heat from the planet's interior could keep the temperatures above 0 °C, and thus water could exist as a liquid.

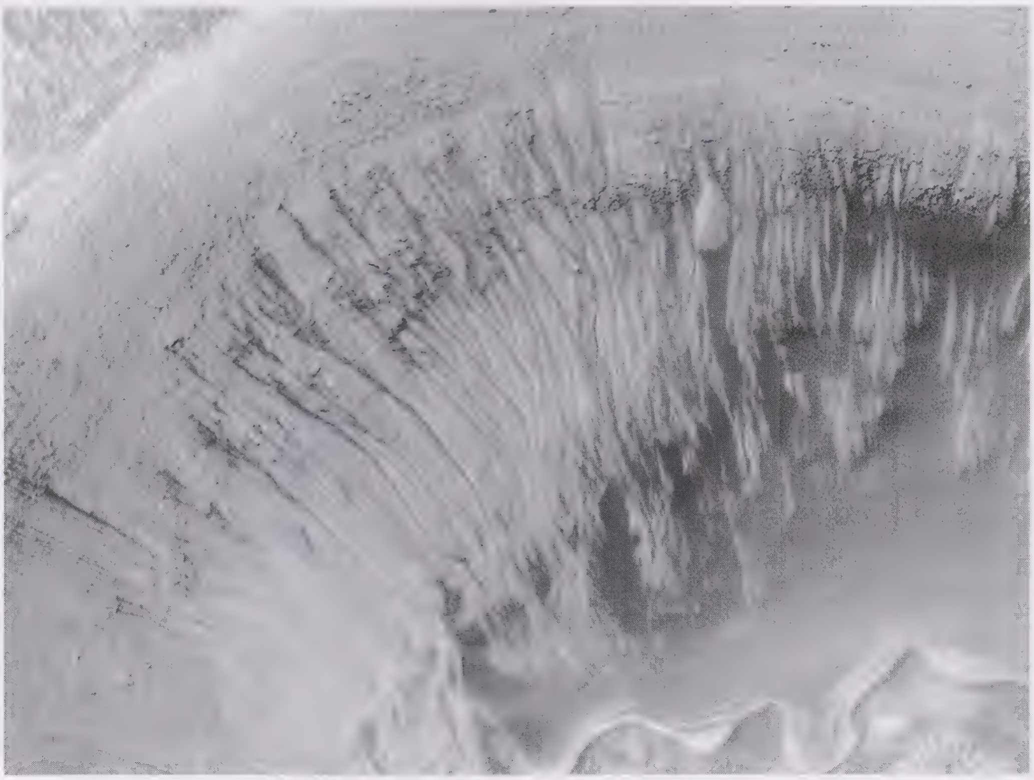


Figure 6.3 Gullies in the northern wall of a 7 km-wide crater in the northern hemisphere of Mars, indicating multiple 'flash flood' releases of water and debris less than one million years ago.

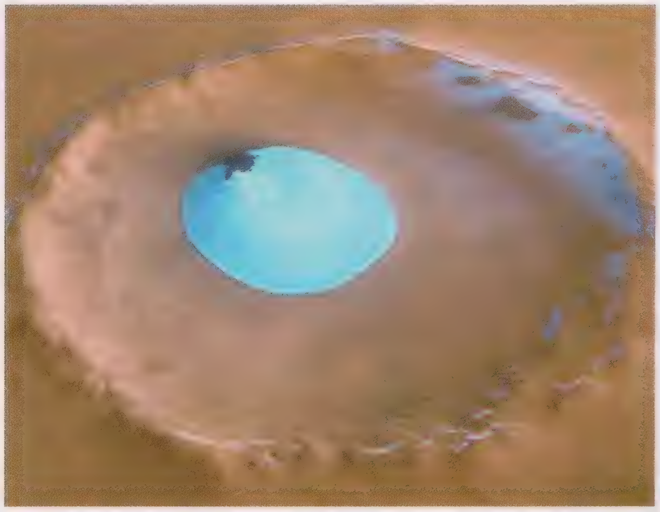


Figure 6.4 A lake of water ice in a crater near the north pole of Mars.

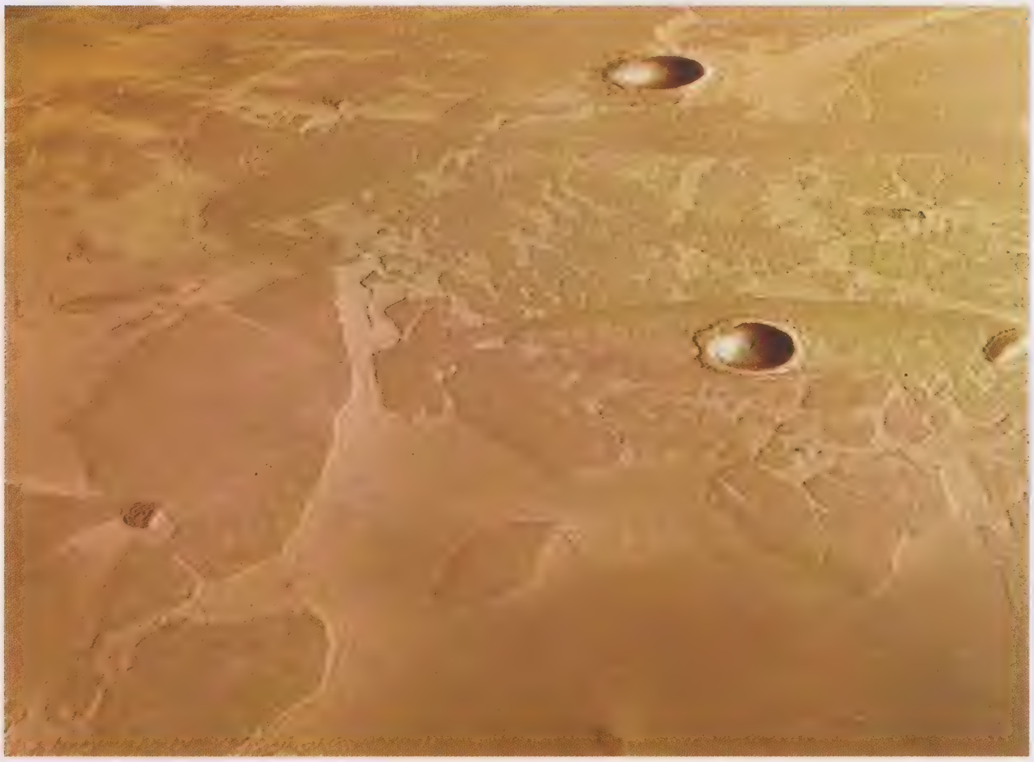


Figure 6.5 Structures resembling ice floes are apparent in this image, a few tens of kilometres across, of part of a vast plain near Mars's equator. Although ice cannot survive long at the surface near the equator, it may have been protected by volcanic dust after a catastrophic flood of the region within the last few million years.

Thus there is a possibility of life existing deep in Mars, just as on Earth where there is life deep in the rocks, provided that liquid water can reach such places. However, most astrobiologists (scientists whose research interests are in extraterrestrial life) consider life deep in Mars to be a remote possibility. By contrast, they consider it much more likely to find evidence of life at the surface of Mars in the distant past, and that evidence for this will be found in the form of fossils or chemical evidence of past life. Although short-lived flows of water have occurred recently, it is the water that appears to have been common as a liquid on the surface in the distant past that may have provided conditions for life to become established. Clement conditions could have lasted long enough for life to evolve, although probably not long enough for it to evolve far beyond the single-cell stage. In the next activity you can explore how ages are established for the various terrains of Mars.

Activity 6.2 Dating the Martian surface

20 minutes

Study Figures 6.2 and 6.5. How do the appearance and relative numbers of craters compare? From your comparison, explain how impact craters could be used to deduce that one terrain on the surface of Mars is older than another. Outline a simple demonstration of your own invention that would illustrate the principle. ◀

Mars hit the headlines in 1996 after a NASA press conference was convened to announce the publication of a scientific paper claiming that biological microfossils had been discovered in a meteorite from Mars known as ALH84001. This claim has been disputed, and the balance of opinion is that the tiny structures, and the accompanying chemical features of the meteorite, have a non-biological origin. Nevertheless, Mars has hardly been explored for evidence of *past* life, which was one of the objectives of the *Beagle 2* lander (developed within the OU's Planetary and Space Sciences Research Institute). This lander was released from the European Space Agency's *Mars Express* spacecraft for a landing on Mars in December 2003. Although no signals were received from *Beagle 2* after landing, more ambitious plans are already under way for a European programme of Mars exploration to complement that of NASA. The first phase includes a lander and a rover carrying experiments to look for signs of present or past life below the surface. The next phase is expected to culminate in the return to Earth of samples from the surface of Mars.

6.3.2 Europa

Europa is one of the four large satellites of Jupiter, the others being Io, Ganymede and Callisto. If you compare the data on the planets and their satellites in the S194 Data Bank, you will see that these four satellites are about the same size as Mercury, so they would be regarded as planets if they were in their own orbits around the Sun rather than in orbit around Jupiter.

However, the fact that these satellites *are* in orbit around Jupiter has led to the possibility of life being found there. This is because the tidal forces of Jupiter can cause varying deformations of bodies in orbit close to the planet. Varying deformations can cause heating as exemplified by a squash ball, which is heated when it is repeatedly deformed by being struck. We shall return to the heating process, called **tidal heating** shortly, but, first, let us see why this heating is important to the prospect of finding life on Europa.

Figure 6.6 shows an image of Europa. Its density indicates that most of its interior must be rocky, but it is covered by bright ice to a depth of probably tens of kilometres. The surface has very few craters and is extremely flat.

- Using your answer to Activity 6.2, why would you deduce that the surface of Europa is very young?
- There are almost no craters on the surface, indicating that the surface material (water ice) has been solid and exposed to bombardment for a relatively short time.

The reddish linear features are cracks and ridges, thousands of kilometres long. Mottled, reddish 'chaotic terrain' exists where the surface has been disrupted and ice blocks have moved around (see also Figure 6.7). The paucity of craters,

together with these other features, has led scientists to conclude that there could be an ocean of liquid water beneath Europa's surface. Heat from radioactive decay in Europa's interior, supplemented by tidal heating, provides the energy to keep the ice molten at depth. The red material at the ridges and chaotic terrain is a non-ice contaminant and could be salts brought up from this possible ocean beneath the frozen surface. Figure 6.7 shows where the icy surface has been broken up into ice-rafts that floated apart until the water between them froze.

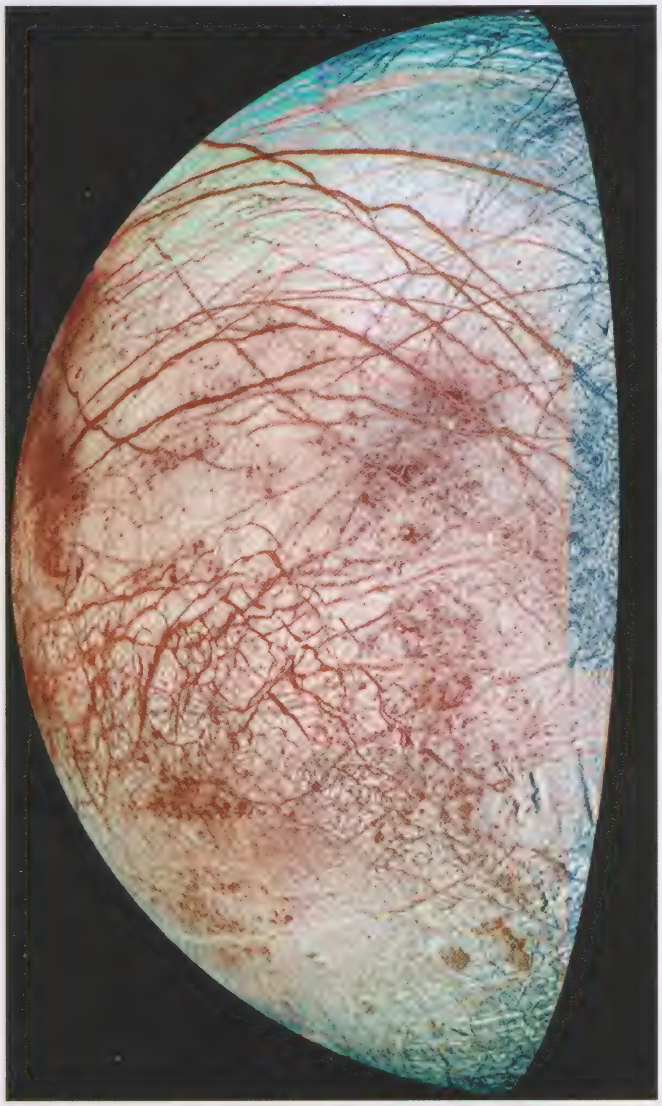


Figure 6.6 An image of Europa with the colours enhanced to show extra detail.

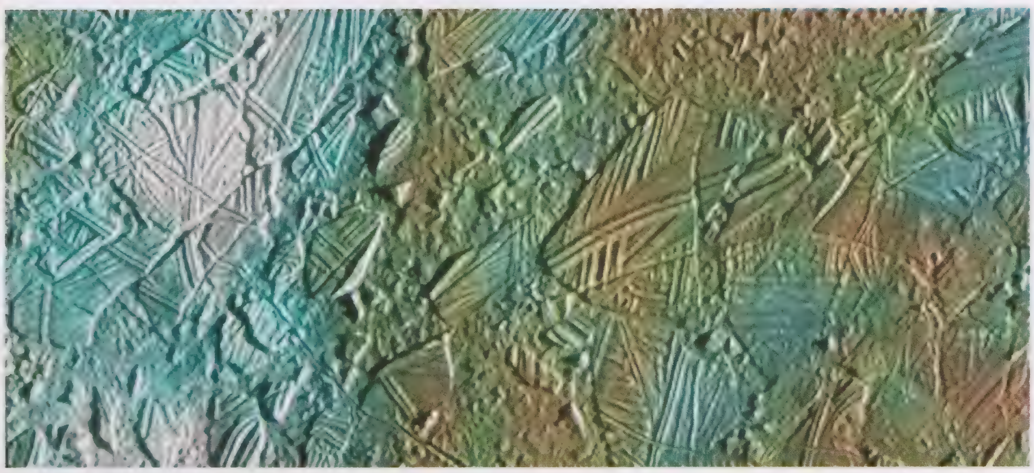


Figure 6.7 Close-up image of part of Europa, showing blocks of ice that appear to have drifted before being frozen into their current positions.

In that widespread ocean aquatic life-forms could exist today. It would be an extremely ambitious mission to send a spacecraft to land on Europa and drill through the ice to make direct measurements, but missions to Europa are a high priority in the future plans of both the European Space Agency and NASA.

To understand how Jupiter causes the varying deformation of Europa that leads to the tidal heating, consider a very large, spongy ball falling towards Jupiter because of the gravitational attraction between the ball and Jupiter. Figure 6.8a shows the situation, where you can see that the ball really is *very* large! The ball can be notionally (not actually) divided into pieces of equal mass. This can be done in any way – Figure 6.8a shows two pieces of equal mass shown as red dots, one on the side nearest to Jupiter, and one on the side furthest from Jupiter. The force of gravity between two objects decreases as the distance between them increases.

- So, on which of the two red dots will the force of Jupiter's gravity be greater?
- It will be greater on the dot nearer to Jupiter.

This will result in the two dots being pulled apart. The ball as a whole is distorted as shown in Figure 6.8b, the shape resembling that of a rugby ball (or an American football). Because the distortion arises from a difference in gravitational force across the ball, it is called a *tidal distortion*, and the bulges are called *tidal bulges*.

To keep the ball orbiting around Jupiter it would have to be moving sideways, just as in the case of the Moon in orbit around the Earth, as described in Section 3.3. However, this does *not* alter the tidal distortion. Suppose that the ball is in a circular orbit and always keeps the same face towards Jupiter, just as the Moon keeps the same face towards the Earth. In this case, the tidal bulges will always lie on the line from the ball to Jupiter, as in Figure 6.8c. The distortion, from the point of view of the ball's interior, is fixed, so there would be no tidal heating. In fact the effect of tidal forces causes the rotation periods of large moons to match their orbital periods; this phenomenon is called **synchronous rotation**.

To understand tidal heating, consider the ball to be in an elliptical orbit around Jupiter, as in Figure 6.8d. For the moment, suppose that the tidal bulges always lie on the line from Europa to Jupiter. You can see that there is a smaller tidal distortion the further the ball is from Jupiter. This is because not only does the gravitational force decrease with distance but so does the difference in gravitational force across an object.

- If the ball is at an infinite distance from Jupiter, what is the difference in the gravitational force of Jupiter across the ball?
- The gravitational force due to Jupiter is zero at all points on the ball, so the difference is also zero.

This variation in tidal distortion as the ball goes around its orbit is rather like cycling the degree of distortion of a squash ball, and so there is tidal heating.

There is another contribution to the tidal heating because the tidal bulges on the ball do not stay in line with the direction to the planet. This is a result of the

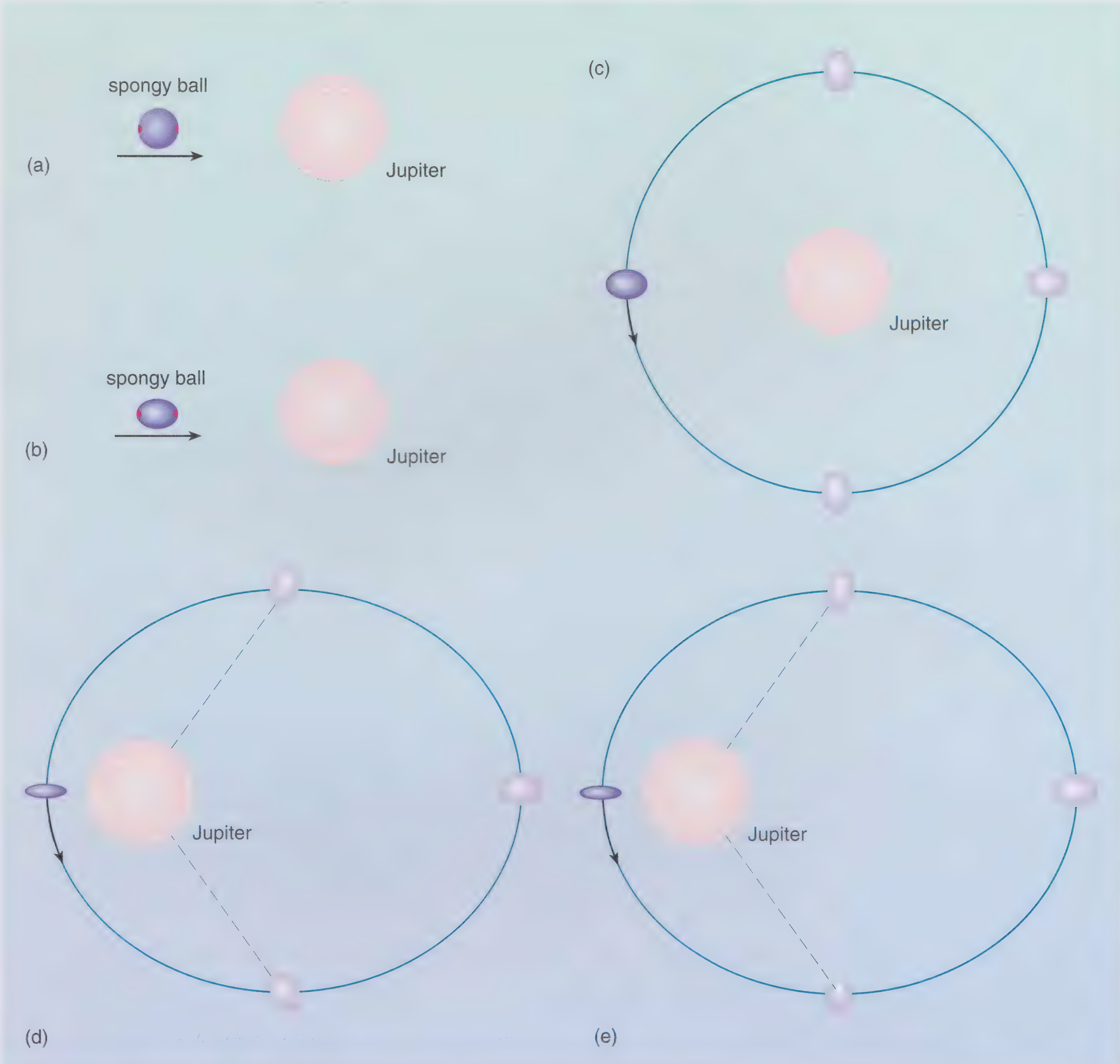


Figure 6.8 (a) A large, spongy ball falling towards Jupiter. (b) The distortion that would occur in the ball. (c) The ball in a circular orbit around Jupiter, and keeping the same face towards Jupiter. (d) The ball in an elliptical orbit around Jupiter with the tidal bulges lying on the line from Jupiter. (e) As (d), but with the tidal bulges failing to keep alignment. The effects are exaggerated to make them visible.

combination of two different effects. The rotation of the ball tends to pull the tidal bulges out of alignment because of frictional forces (Figure 6.8e). In addition, in an elliptical orbit, the orbital speed is not constant, but is greatest when the ball is closest to Jupiter. The direction to Jupiter therefore changes for any given position on the surface of the ball which spins at a constant rate.

Europa has an elliptical orbit around Jupiter so these effects can cause tidal heating. You might wonder whether tidal heating can make other satellites of the giant planets into potential habitats. We need to concentrate on large satellites – the temperatures of small satellites cannot be raised much by tidal heating or by any other form of heating. The reason is that the smaller a body, the greater its surface area per unit of its mass, thus leading to more rapid loss of heat by radiation to space. In order of distance from Jupiter, the large satellites are Io, Europa, Ganymede and Callisto. Io is thus closer to Jupiter than Europa, and it is heated even more strongly. It is heated so much it has a highly volcanically active surface devoid of water. Ganymede and Callisto are further away and the tidal forces are consequently smaller. However, astronomers believe both Ganymede and Callisto may also have subsurface oceans of electrically conducting salt water, based on measurements of their effect on magnetic fields. Since tidal forces alone are insufficient to melt the ices, melting is believed to be the result of trapped heat from the decay of radioactive materials in the rocky cores of these bodies. The large satellites of Saturn, Uranus and Neptune are also insufficiently heated by tidal forces for melting to occur although subsurface oceans cannot be ruled out for the largest.

6.3.3 Life in extreme environments

The search for life on other planets is necessarily constrained by what is known about life on Earth, since it is the only example we have. To help guide the search for life, scientists visit environments on Earth that in one way or another (in some physical or chemical extreme) resemble extraterrestrial environments.

The cold deserts of Antarctica offer insights into how life can survive in extremely cold conditions. As the average temperature on Mars is about –55 °C, this might be a good place to understand how organisms produce chemicals that help them survive freezing and thawing. In the hot deserts of Chile, the extreme desiccation helps scientists understand how life might survive on the surface of planets where liquid water is very scarce. As liquid water is extremely scarce near the surface of Mars, if there is any life there, it would certainly have to be able to cope with desiccation.

When scientists go to these environments they look for protected habitats – places where life might have some opportunity to survive the extreme conditions and flourish in environments that are otherwise hostile to life. An example of such habitats is 'cryptoendolithic' habitats – literally habitats hidden within rocks. Some micro-organisms can invade the cracks and pore spaces within the rocks and live within the material. You can see an example in Figure 6.9. This is an example of a cryptoendolithic community of cyanobacteria living in a rock in the Arctic. The micro-organisms are photosynthetic, which means they need light for their energy needs. As you can see, they have to grow at a depth in the rock where the light levels are enough for photosynthesis. Too low and they don't get enough light. By growing inside the rock, they escape the extremes of the surface of the rock, which include exposure to solar ultraviolet radiation and desiccating winds. The result is a distinct band of growth within the rock where the organisms can flourish.

Figure 6.9 A cryptoendolithic community of cyanobacteria (arrowed) living in a rock from the Arctic.

These habitats in rocks are found in many extreme deserts of the world, both hot and cold. In addition to living in rocks, micro-organisms can also live under rocks, where they get the same protection from environmental extremes. As photosynthetic micro-organisms need light, to live under a rock requires that the rock itself is translucent – allowing sufficient light to penetrate through the rock to the micro-organisms beneath. Quartz is a common rock that is colonised on its underside in extreme deserts. Organisms that live on the underside of rocks are called ‘hypoliths’. Of course, we cannot say that such habitats are colonised on other planets such as Mars, but studies on these habitats can reveal how life survives in extremes on Earth and whether there is any likelihood of life surviving the extremes that are found elsewhere.

The search for so-called ‘analogue’ environments is revealing many facts about life on Earth. Several decades ago, it would have been inconceivable that life existed in the deep oceans and even in the clouds. However, studies of these environments and many others have revealed the remarkable versatility and tenacity of micro-organisms – their ability to harness energy supplies in the form of light and chemical compounds and their ability to survive and grow in extremes of temperature, acidity, salinity and radiation, among other extremes. In turn, these studies are aiding scientists in the search for life on other planets.

6.4 Potential habitats beyond the Solar System

Beyond the Solar System astronomers look to the planets and satellites of other stars as potential habitats. However, there is a practical difficulty. Distances within the Solar System are relatively small, so spacecraft have been sent to all the Sun’s planets, and telescopes on Earth and in Earth-orbit have established much about the atmospheres and surfaces of those planets and their satellites.

Travelling beyond the Solar System, however, involves far larger distances that cannot be easily crossed, even in many human lifetimes.

- How much further from Earth is the nearest star (Proxima Centauri) than Pluto?
- In Section 4.2 the distance to the nearest star (Proxima Centauri) is given as about 4×10^{13} km, and in Section 3.2 the distance to Pluto is given as 5.9×10^{9} km. Therefore, the nearest star is about 4×10^{13} km/5.9×10^{9} km times further away, which is nearly 10^{4} times.

At such distances, it is difficult to see planets directly. This is because a planet's feeble light is easily drowned by the much greater light of its star, which is always closely aligned with the planet. It is rather like trying to detect the light of a glow-worm alongside a searchlight from a distance of many kilometres.

Since often the planets of other stars cannot be detected directly, we must search for them indirectly, through the influence they have on the stars they orbit. One effect is on the motion of the star, as illustrated in the face-on view in Figure 6.10. As the planet moves along its relatively large orbit, its parent star is forced to perform a tiny orbit over the same period of time. (You will see how this happens when you do Activity 6.3, and you will learn how such motion might be detected in Chapter 7.) Now, many stars are easily observed, and several move in ways that reveal the disturbing influence of one or more planets. About 150 planets were discovered by such indirect methods between 1995 and 2005, when the first direct detections were achieved.

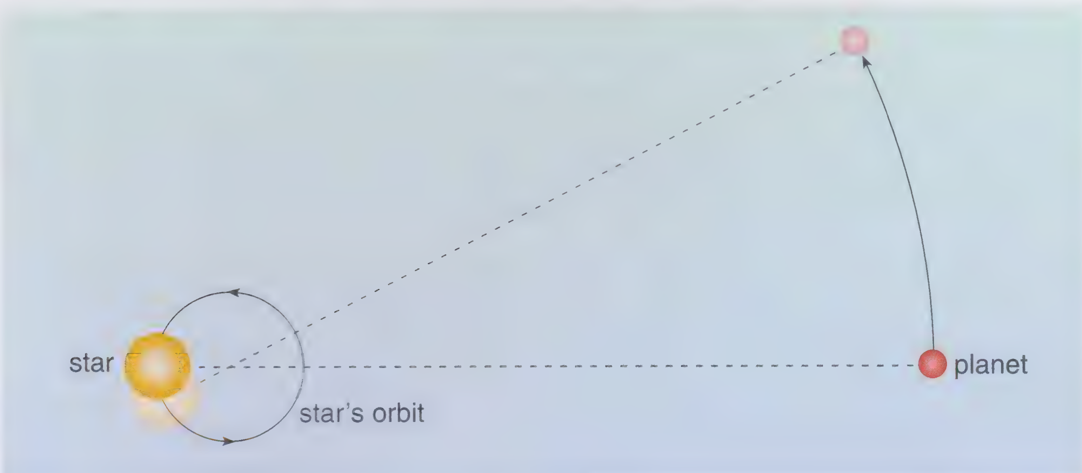


Figure 6.10 The orbital motion of a star in response to that of a massive planet.

Activity 6.3 Motion of two bodies around each other

20 minutes

In Activity 3.1 you whirled a light object (such as a cork) round on a piece of string. Repeat that demonstration now, and note that your hand (the 'star') hardly moves as the object goes round its circle. Now replace the object with something much heavier. Take care that no one will be hit by the object as you whirl it and that, should you inadvertently let it go, it won't harm any person or property. When you whirl the heavy object you should find that your hand (the 'star') now has to go round a somewhat larger orbit.

A similar large motion occurs when you face someone, hold hands at arm's length and whirl around. Neither of you will be able to turn on a fixed spot – you will both go round an orbit.

In these demonstrations gravity has been replaced by tension in the string or your arms but the insight should be useful.

Planets that orbit stars other than the Sun are called **exoplanets**. Most of the exoplanets discovered by optical methods in the first ten years of such discoveries have been within a few hundred light years of Earth – in our back yard in terms of interstellar distances. The majority of those planets are at least as massive as Saturn, and many of them are very close to their parent star. This was inevitable; massive planets in tight orbits around nearby stars are the easiest to detect by the method described here. However, lower mass exoplanets have been detected, and some exoplanets have been found by other techniques, including radio and infrared methods, or by the use of *transits* in which a star is periodically dimmed as a planet passes across it. There are detailed lists of the exoplanetary systems so far discovered on the internet: see the S194 Data Bank for appropriate references.

At least a few of the nearby Sun-like stars have planetary systems. If this proportion is typical of the stars that can be seen at a dark site with the unaided eye, at least several hundred of the visible stars will have planetary systems. Unfortunately, until images of these planets and their satellites are obtained, we can't tell whether they are inhabited. It will be about 2010 at the earliest before we have the instrumental capability to obtain such images. Then, if a planet is there, it will be imaged, although only as a single dot of light. So the question arises: 'How could we tell from such an image whether a planet is inhabited?'

6.4.1 Planetary spectra

The only way of telling whether a planet is inhabited is from its spectrum. The basic sorts of spectra (continuous, absorption and emission) were introduced in Figure 1.5, along with a way of viewing them. Consider first what we could learn from the *continuous spectrum* of a planet. Taking the Earth as an example, we shall consider the spectra of the Earth that have been obtained from space.

Examples of continuous spectra are shown in Figure 4.8. The spectrum of the Earth has broadly the same shape but at far longer wavelengths.

- What is the name given to the wavelength range on the long wavelength side of the visible range?
- The answer is infrared.

The Earth's spectrum is concentrated at infrared wavelengths. These are emitted by the surface and the atmosphere – if we had infrared eyes the Earth's surface and the atmosphere would seem to glow!

- What do the wavelengths of emission from the Earth tell you about the Earth's average surface temperature, compared with those in Figure 4.8?
- Comparison with Figure 4.8 shows that the Earth's surface must be a lot cooler than 2750 °C!

In fact, we can infer that the Earth's average surface temperature is about 15 °C. From other information in the spectrum (well beyond the scope of this course) the surface pressure can also be estimated, and we find, from our vantage point in space, that the pressure and temperature at the Earth's surface are suitable for water to be liquid. But can we tell whether water is present? Yes we can, from the absorption features in the spectrum.

Figure 1.5 shows an absorption spectrum, where material in an absorbing cloud has depleted the light at certain wavelengths. From the wavelengths of these absorption lines it is possible, in principle, to determine the composition of the cloud. Likewise, the infrared spectrum of the Earth also shows absorption lines from absorption in the Earth's atmosphere. Some of these show that water (H_2O) is present as a gas (vapour) in the atmosphere. It is even possible to tell that there is so much H_2O present that some of it must have condensed on the surface, where it would be predominantly in liquid form rather than solid ice. Thus we have the first requirement for life – liquid water – and it follows that the average surface temperature is low enough for huge carbon compounds to be stable. The presence of carbon is indicated by other absorption lines such as those caused by carbon dioxide (CO_2) in the atmosphere.

We can thus establish that the conditions for carbon–water life exist on the Earth, but we have not yet shown that life is actually present. A strong indication is an absorption line caused by ozone (O_3). Through chemical processes in the atmosphere this is derived from O_2, the oxygen that we breathe; O_2 does not have strong lines in the infrared spectrum. This does not matter – from the ozone line we can establish that oxygen as O_2 is a major constituent of the Earth's atmosphere. Oxygen is such a reactive substance that it would rapidly disappear from the atmosphere unless it was being regenerated very rapidly. The best way of accomplishing this is photosynthesis by green plants and other organisms.

In **photosynthesis** an organism starts building its body tissues, which include complex carbon compounds, from simple molecules, namely carbon dioxide and water. An energy source is required, and most types of organisms use solar radiation. Oxygen (O_2) is produced as a by-product by most types of photosynthesising organisms. Without photosynthesis, the O_2 content of the Earth's atmosphere would be *far* lower. Thus the ozone absorption feature indicates strongly that the Earth is inhabited.

In the case of planets around other stars, we should be able to establish whether liquid water exists at the surface and, therefore, whether the surface conditions are suitable for carbon–water life. If there is an ozone absorption feature we could be fairly confident that life is present. We would be more confident if other absorption features were present, but details cannot be given here.

Unfortunately, ozone could be below detectable limits even if life is present for any one or more of three reasons.

1. Local life-forms do not photosynthesise.
2. Local life-forms do photosynthesise but oxygen is not released (there are some terrestrial organisms for which this is the case).
3. The rate of release of oxygen is so slow that the atmospheric abundance, in the face of removal processes, remains low.

However, even if there were no ozone line, there could be other groups of absorption lines that would indicate the presence of life. Astrobiologists have identified such groups, but there is (again) no room here for details.

To conclude: we can say with some confidence that the next 20 years or so should resolve the issue of whether life is common in our part of the cosmos.

6.5 Chapter summary

The essential points of Chapter 6 are as follows.

1. All life-forms on Earth are based on complex carbon compounds, and require liquid water during at least part of their life cycles.
2. In looking for extraterrestrial life, attention should focus on places where huge, complex carbon compounds and liquid water could exist, the possible existence of liquid water being sufficient in practice.
3. Within the Solar System, Mars and Europa are the best candidates for finding extraterrestrial life. At the surface of Mars today water can persist only as a solid, and there is no evidence for life on the Martian surface. There might be life deep underground, where water could exist as a liquid. In the distant past, conditions on Mars were different, and liquid water could have persisted at the surface. Life might have evolved then, and so we might find fossils.
4. Europa is a rocky world overlain by an ocean of water and topped by a thin crust of ice. The water is maintained as a liquid through tidal heating. There might be aquatic life-forms in the oceans.
5. Beyond the Solar System astronomers look to the planets of other stars. Many nearby stars are already known to have planetary systems. This represents a few per cent of the nearby Sun-like population, and this proportion can only grow. As we discover more exoplanets, their spectra will enable us to look for signs of life.

6.6 End-of-chapter questions

Question 6.1 It has been suggested that, at temperatures too high for complex carbon compounds, life might be based on silicon. In one or two sentences, make an 'educated guess' about why chemists think this is unlikely. ◀

Question 6.2 As the Sun ages, its luminosity (power output) will gradually increase considerably. Explain why the Earth will eventually become uninhabitable. ◀

Question 6.3 If Europa were in its own orbit at its present distance from the Sun, rather than in orbit around Jupiter, why would it be removed from the list of possible habitats for life today? ◀

Question 6.4 If there were no life on Earth, explain one way in which the infrared spectrum of the Earth would be different. ◀

Question 6.5 If a spectrum was obtained of a planet considerably colder than the Earth, how would the spectrum differ from the Earth's? ◀

7 Galaxies

7.1 Introduction

In this chapter you will meet some of some of the most majestic objects in the Universe. You will also revisit some of the key ideas that were introduced earlier: *angular size* and *scientific notation*, which are used not just in astronomy but also in many other areas of science; *electromagnetic radiation*, without which there would be no astronomy; and the mysterious *dark matter* that was briefly mentioned in Chapter 1.

7.2 The Milky Way galaxy

In Activity 4.2 you might have seen the Milky Way – the faint band of milky light that arches across the sky. This faint light comes from millions of distant stars and nebulae that make up a huge disc. That disc is the most visible part of the **galaxy** in which we live, a galaxy that is also referred to as the **Milky Way**. Figure 7.1 is an impression of the visual appearance of the Milky Way galaxy, as might be seen by observers living in other galaxies.

The most obvious component of the Milky Way is the great **disc** of stars that contains the Sun. The disc is about 10^5 light years in diameter and a few thousand light years thick. It contains about one hundred billion (i.e. 10^{11}) stars, many of the youngest and brightest being concentrated in the swirling *spiral arms* that contain many sites of active star formation. The Sun is situated about midway between the edge of the disc and the centre, in what appears to be a small branch or spur leading off from one of the major spiral arms. In the middle of the disc is the Milky Way's second major component a thickened **bulge** of stars that is elongated into a bar. The whole of the disc, together with its central bar, is embedded in the Milky Way's third visible component: an extended **stellar halo**. This gets its name from the billions of faint stars that it contains, but it also houses an extensive body of very hot gas, as well as the Milky Way's retinue of 150 or so *globular clusters*. (These dense spherical gatherings of ancient stars were discussed in Chapter 5.)

In addition to the visible components described above, most astronomers believe that there is also an invisible component of our galaxy that is bigger and more massive than all the visible components combined. There are several independent lines of argument that indicate the existence of this fourth component, but one of the most compelling concerns the gravitational pull of the Milky Way. The combined gravitational pull of all the stars and gas clouds in the visible parts of the Milky Way is simply not sufficient to hold the outermost stars and gas clouds in their orbits. What can account for the overall stability of the Milky Way if the disc, bar and stellar halo are not enough? The answer favoured by most astronomers is another halo, usually called the **dark halo**, which is at least as extensive as the stellar halo, but far more massive, and entirely composed of some kind of matter that emits no visible light, nor any other kind of detectable radiation. This non-luminous matter, currently detectable only through its gravitational influence on the matter that we can see, is called *dark matter*.

(a)

(b)

Figure 7.1 An impression of the visible parts of our home galaxy, the Milky Way: (a) face-on; (b) edge-on.

The precise nature of dark matter is one of the outstanding mysteries of modern astronomy. There are good reasons for believing that it cannot be composed of the sorts of particles that make up ordinary atomic matter, so some more exotic kind of particle may be involved. Many astronomers have become convinced that dark matter is composed of relatively massive particles that are uncharged and interact so feebly with ordinary matter that no laboratory-based experiment has ever detected them. If dark matter really does consist of these weakly interacting massive particles (usually called WIMPs for short) there could be some of them passing through your body as you read this. Of course, it is possible that there are no WIMPs, and perhaps even no dark halo, but in that case something even more exotic seems to be needed to keep the Milky Way's outermost stars in their orbits.

To gain further insight into the nature of the Milky Way, you should now look at the relevant section of the S194 Image Bank. In particular, note the evidence for the existence of a very massive black hole at the centre of our galaxy; this is one of the most dramatic of all the recent discoveries about the Milky Way.

7.3 Other galaxies

Figure 7.2 was obtained with the Hubble Space Telescope: it shows many distant galaxies. Such images indicate that the total number of galaxies in the visible part of the Universe is very roughly equal to the number of stars in the Milky Way, i.e. about 10^{11}. These other galaxies come in a wide range of shapes and sizes. The largest known galaxies contain about ten times as many stars as the Milky Way; the smallest are very faint and hard to observe, but they seem to contain fewer than a million stars, although it is difficult to know exactly what constitutes the 'smallest' galaxy.

Figure 7.2 Some distant galaxies.

Relatively few galaxies have been given individual names, so particular galaxies are often referred to by their identification numbers in catalogues of astronomical bodies. The most famous of these catalogues is probably the list of 110 non-stellar objects, compiled by the eighteenth-century French astronomer, Charles Messier. About 40 of Messier's objects are galaxies, including M31 and M82. The next most famous catalogue is the New General Catalogue (NGC), which lists the positions and vital statistics of 7840 objects, with a further 5386 in its supplementary Index Catalogue (IC). M31 and M82 both appear in the New General Catalogue, where they are known as NGC224 and NGC3031, respectively. Several other catalogues are also in use but, when all else fails, a galaxy can always be identified by its coordinates in the sky. (See the S194 Data Bank for references to online catalogues.)

- Older astronomy books tend to define the term 'galaxy' along the following lines. 'A galaxy is a vast assembly of luminous matter, possibly containing billions of stars, held together by the mutual gravitational attraction of its constituents.' On the basis of what you have read, propose a modified definition that is more in keeping with modern views concerning dark matter.

- A galaxy is a vast assembly of dark matter and luminous matter, possibly containing billions of stars, held together by the mutual gravitational attraction of its constituents.

The rest of this chapter concerns some of the characteristics of the many galaxies that can be observed, including their division into classes according to shape, their internal movements, the possible effect of giant black holes at their centres, and even a little about their origin and evolution. However, before studying any of those topics in detail you should work through the section of the S194 Image Bank devoted to 'other galaxies'. The images there will give you the 'observational' background that you need. As you examine the images and read the captions, take care to note any information about angular sizes, since that is the first subject we shall consider. Consult the Image Bank now.

Galaxies are enormous objects. Their visible parts are typically tens or hundreds of thousands of light years in diameter. Yet many images of galaxies show objects that have angular sizes of just a few arcmin or less. This reflects the very great distances of those galaxies – for a galaxy the size of the Milky Way to have an angular size of only a few arcmin, it must lie at a vast distance from Earth.

- What is the relationship between the units arcsec, arcmin and degree, which are used to measure angles?

- As you saw in Chapter 2, there are 60 arcmin in 1° and 60 arcsec in 1 arcmin and hence 3600 arcsec in 1°.

- Suppose an astronomer observes two galaxies, one (A) with angular size 2 arcmin and another (B) with angular size 30 arcsec. If their overall appearance suggests that the two galaxies are very similar and hence likely to have about the same diameter in light years, what can you say about the distances of the two galaxies?

- The angular size of galaxy B is one-quarter that of galaxy A (2 arcmin is 120 arcsec), so B is more distant. More specifically, galaxy B is about four times the distance of galaxy A.

Note that this line of reasoning gives astronomers a way of gauging *relative* distances. If two galaxies are thought to be the same size, their relative distances can be found from their angular sizes alone. But this is a big 'If': galaxies come in a wide range of sizes so the assumption that two are the same size must be based on more than a superficial similarity.

- Supposing that galaxies A and B (above) both have a visible diameter of 100 000 light years, what are their respective distances?
- Using the (approximate) relationship between distance, diameter and angular size that was discussed in Chapter 2: distance of galaxy = 57 × (diameter of galaxy ÷ angular size of galaxy in degrees). Thus, for galaxy A, which has angular size 2 arcmin = 2/60 degree = 0.0333 degree: distance of A = 57 × (100 000 light years ÷ 0.0333) = 1.7×10^8 light years. Galaxy B is four times as far away, at 6.8×10^8 light years.

- As well as galaxies A and B having different angular sizes, what other difference would be observed between galaxies A and B?
- Galaxy A would appear brighter than galaxy B. If galaxy B's distance is about four times that of A then A's apparent brightness will be about 4 × 4 (i.e. 16) times that of B.

7.3.1 Classifying galaxies

Most galaxies can be usefully classified according to their observed shape. Several different classification schemes are in use but the one described here is the **Hubble classification scheme**, one of the oldest and most common. In the Hubble scheme a galaxy is primarily classed as *elliptical*, *lenticular* (i.e. lens-shaped), *spiral* or *irregular*. The spirals and lenticulars each contain visible stellar discs and may be additionally classed as *barred* or *normal*, according to whether or not the central stellar bulge is an elongated bar. The ellipticals and spirals are subdivided into several 'types', depending on the finer details of their appearance. The overall scheme, including the abbreviations used to represent each class and type, is illustrated in Figure 7.3.

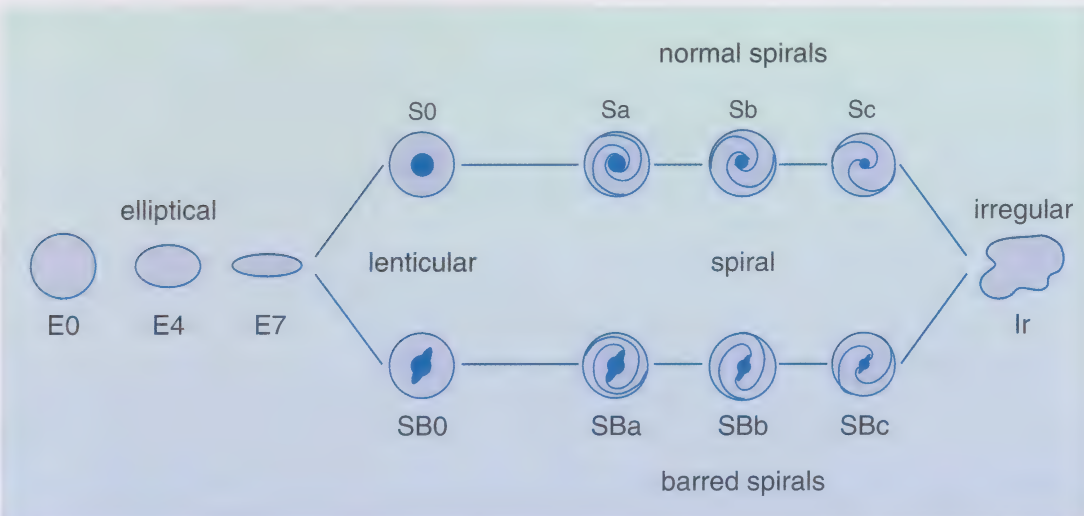


Figure 7.3 The Hubble scheme for the classification of galaxies.

Activity 7.1 Classifying galaxies

Review the captions of the images in the 'other galaxies' section of the S194 Image Bank. Use the information they contain, together with Figure 7.3, to list the distinguishing features of elliptical, lenticular, spiral and irregular galaxies. Write down the detailed features that distinguish an Sa galaxy from an Sc galaxy. How does an E4 differ from an E7? To which class and type does the Milky Way belong? ◀

20 minutes

One important characteristic that distinguishes the various classes of galaxies concerns their star-forming activity. Spiral and irregular galaxies exhibit bright regions of active star formation, whereas ellipticals do not. This has implications for the composition of those classes of galaxies.

- What does the lack of active star formation suggest about the content of elliptical galaxies? In what key ways would the night sky look different if we lived in an elliptical galaxy?
- Stars form from gas clouds in the interstellar medium (ISM). The absence of sites of active star formation in elliptical galaxies suggests that they contain little or no ISM. If we lived in such a galaxy we would still see stars, but there would be no band of light comparable to the Milky Way, and no nebulae comparable to the Orion Nebula or the Trifid Nebula. Furthermore, the bright and massive short-lived stars that feature prominently in our night sky would also be absent.

Interpreting pictures of three-dimensional objects

We are all accustomed to looking at pictures of three-dimensional objects, such as people's heads, and forming a clear idea about what the whole object looks like even though the evidence we have only relates to a single viewpoint. This is a useful skill that is partly built on our past experience of looking at similar objects. However, when dealing with scientific images, it is important to extract as much information as possible from an image, but not to read into it more than is there. Speculation about what might be in an image is not necessarily bad, but you must be clear about the point at which observation stops and speculation begins.

Examining pictures of galaxies is fertile ground for developing several interpretive skills. For example, what shape are elliptical galaxies? A particular image may have an elliptical outline, and may be classified as being somewhere in the range E0 to E7, according to the relative lengths of the long and the short axes of the observed ellipse, but what would such a galaxy look like if it was rotated through 90°? What are the true three-dimensional shapes of elliptical galaxies and to what extent can they be discerned from two-dimensional images?

Try a little experiment. Pick up a pen and look at it end on. What shape do you see? If it's a normal pen, probably a circle, rather like an E0 galaxy. Now look at the pen sideways on. What kind of elliptical galaxy does it most resemble? It may not look much like any elliptical galaxy, but it's probably closest to a 'cigar-shaped' E7 galaxy. Hold the pen horizontally,

in front of your eyes and rotate it from the 'sideways' view to the 'end-on' view. Can you see it pass through the stages where it looks like an E5 and an E3? An E0 galaxy has a circular appearance. Does that mean it is really a spherical gathering of stars, or might it be an end-on view of a cigar-shaped distribution?

A pen is a solid object and light is reflected from its surface, which makes it easier to interpret the pen as a three-dimensional object rather than an 'outline'. Elliptical galaxies are different. They emit light rather than reflect it. It is possible to work out the three-dimensional shape of some elliptical galaxies, but doing so generally requires detailed studies of the movements of stars within that galaxy, together with some assumptions about the way those motions influence the overall form of the galaxy. On the basis of detailed studies, astronomers have evidence that some elliptical galaxies are ellipsoidal; that is they will have an elliptical appearance from every direction but the detailed form of the ellipse may change with the direction of view. A full appreciation of the shape of an elliptical galaxy is unlikely from any single image of that galaxy.

Similar comments apply to spiral and lenticular galaxies, which are generally seen as inclined discs. In some cases these may even be difficult to distinguish from elliptical galaxies!

Always keep in mind the distinction between the true shape of an object, and the shape it appears to have from a particular viewpoint, especially if it is illuminated in a way that is unfamiliar.

7.3.2 Moving galaxies

Movements taking place within galaxies can be partly determined by studying galaxy spectra, particularly through a general phenomenon associated with waves, called the **Doppler effect**. The basic idea is very simple: imagine an observer detecting radiation of some particular wavelength coming from a stationary source. Now imagine the source moves away from the observer; this will have the effect of 'stretching' the waves, causing the observed wavelength to increase. (You may have noticed this effect in connection with the sound waves radiated by an emergency vehicle as it rushes past – when it is receding the sound of its siren has a lower pitch, indicating a longer wavelength, than when it is approaching.) In the case of visible light radiated from a star or galaxy, such an increase in wavelength causes the familiar pattern of spectral lines to be shifted towards the longer wavelength or red end of the spectrum, and is therefore called a **redshift** (see Figure 7.4). The amount of redshift in the spectrum of radiation from a moving source is a measure of the speed at which the source is moving away from the observer, i.e. the source's speed of recession.

There is a similar effect when a source of radiation moves towards an observer. In this case the waves are compressed, the observed wavelength of the radiation is reduced, and spectral lines are shifted towards the short wavelength or 'blue' end of the spectrum. The appearance of **blueshift** in a spectrum is therefore an indication that the source of the radiation is approaching, and the amount of blueshift is a measure of the speed of approach.

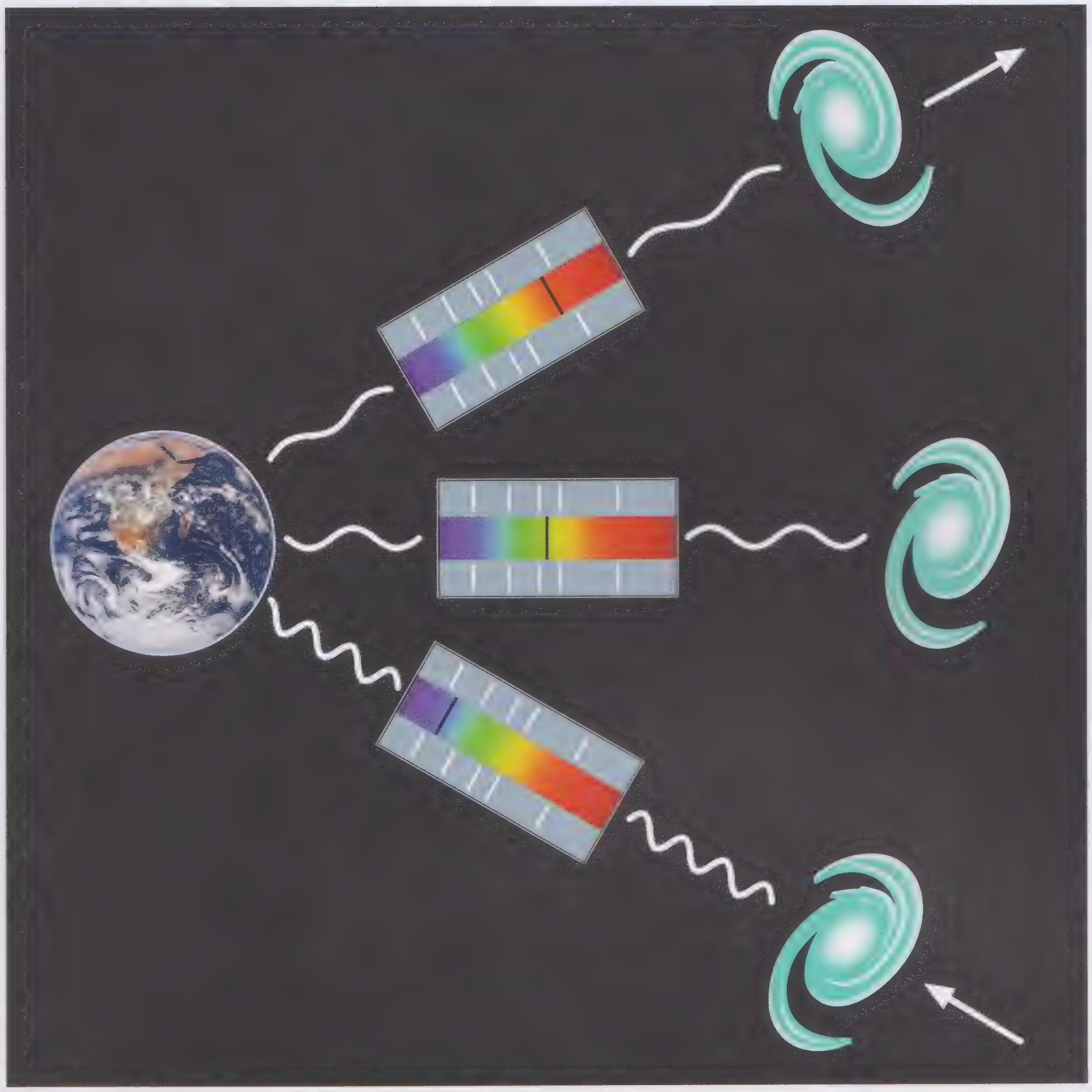


Figure 7.4 The redshift (or blueshift) of a spectral line caused by the recession (or approach) of a moving source of waves.

If a galaxy is sufficiently close that it can be examined in detail, the Doppler effect can be used to study its internal motion as one part moves relative to another part. Such studies reveal that the stars in elliptical galaxies move in a rather chaotic fashion; swarming around each other and giving little indication of any overall sense of rotation. Material in the discs of spiral and lenticular galaxies behaves quite differently. There the stars and gas clouds generally revolve in a single direction around the galactic centre, following nearly circular orbits that lie mostly in the plane of the disc. These orbital speeds can be quite high, possibly reaching hundreds of kilometres per second, but the orbits are so large they still take a very long time to complete. Taking the Milky Way as an example, the Sun moves at about 215 kilometres per second relative to the galactic centre, yet each complete orbit takes about a quarter of a billion years. Other stars, at greater or lesser distances from the galactic centre, may complete their orbits more or less quickly; since the disc is not rigid, there is no requirement for everything to keep in step.

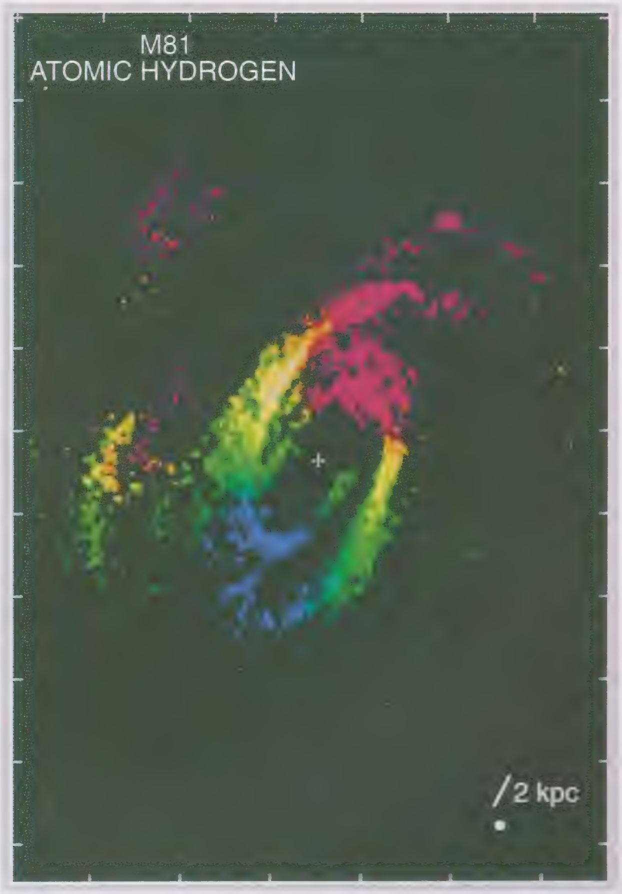


Figure 7.5 Movement in the disc of the galaxy M81. Here, blue indicates parts of the galaxy that are approaching and red those that are receding. Note that this galaxy is tilted with respect to your line-of-sight – you are not looking at it face-on.

Figure 7.5 is a colourful representation of the rotating disc of the spiral galaxy M81. The image is based on observations of radio waves emitted at a wavelength of 21 cm by clouds of hydrogen gas. The red and blue regions show parts of the disc where the normal hydrogen emissions have been redshifted or blueshifted; this indicates recession or approach and gives a clear impression of overall rotation.

In addition to observing motion within galaxies, the movement of galaxies as a whole can be studied, as they move relative to each other. Observations show that some nearby galaxies are approaching the Milky Way (although it will be an immensely long time before there is any chance of a major collision). However, distant galaxies invariably have spectra that are redshifted. It turns out that the redshift observed in these distant galaxies is not just a simple Doppler effect. None the less, it indicates that the distant galaxies are all receding. We shall return to this important discovery in the next chapter.

7.3.3 Peculiar and active galaxies

Some galaxies have odd features that set them apart. Galaxies which have a slight oddity but can still be assigned to a particular Hubble class are called **peculiar galaxies**, their status being indicated by the addition of a ‘p’ to the usual type designation, as in E0p or Sbp. However, some galaxies are so odd that they cannot be placed in any of the usual classes. Figure 7.6 shows how a computer simulation has been used in an attempt to explain the strange shape of the Antenna Galaxy – it seems to be the result of a collision between two spiral galaxies. Many peculiar galaxies are thought to be the result of gravitational

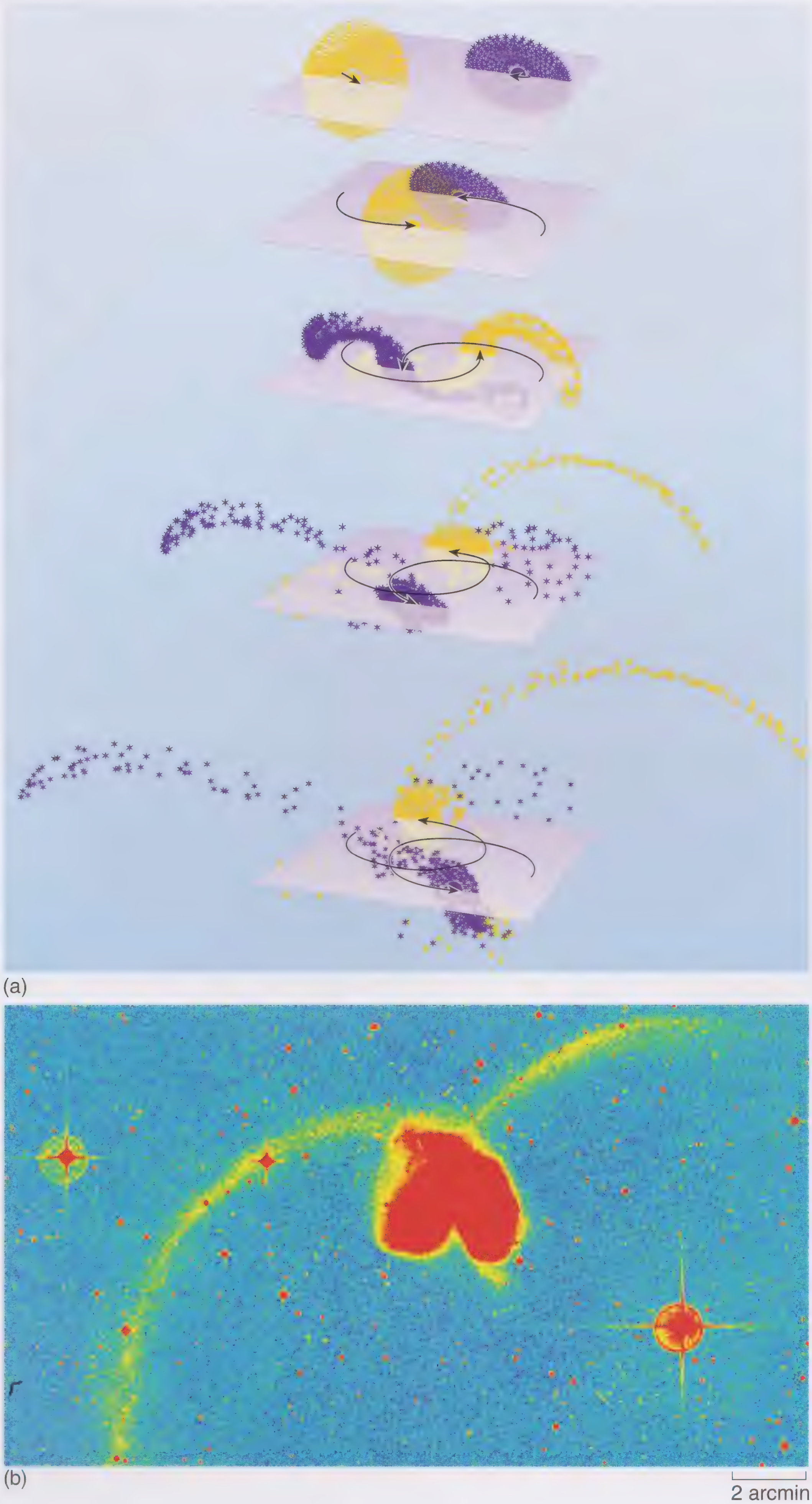


Figure 7.6 (a) A computer simulation of the collision of two spiral galaxies. (b) The Antenna galaxy: probably the result of a collision of the type simulated.

interactions during the collision, merger or even just the close encounter of other galaxies.

A small proportion of galaxies (a few per cent of the total) are known as *active galaxies*. An **active galaxy** produces far more radiation than can be attributed to its stars and gas clouds alone. The brightness of active galaxies can vary significantly over periods of a year or less, indicating that the primary source of their additional radiation is quite small, certainly less than a light year across. The activity is thought to depend on the existence of a supermassive black hole at the galactic centre. Such a black hole would have a mass equal to that of many million, or even a few billion, Suns. No radiation would come from the black hole itself, but matter being drawn into it would become very hot, and the radiation from this hot material would have a strong influence on orbiting gas clouds, and on the total amount of radiation from the galaxy (see Figure 7.7). Variations in the rate at which matter falls into the black hole might account for any observed variations in the brightness of an active galaxy.

There are actually many different kinds of active galaxies. Any detailed explanation of these exotic objects is beyond the scope of this short course, but it is worth noting that the kind known as **quasars** have been observed in very large numbers in recent surveys, Because they are so much brighter than normal galaxies they can be seen out to very great distances, and, clearly, they were more common in the past than they are now. The implications of this finding are, however, still not obvious. Could quasars be the result of some kind of collision

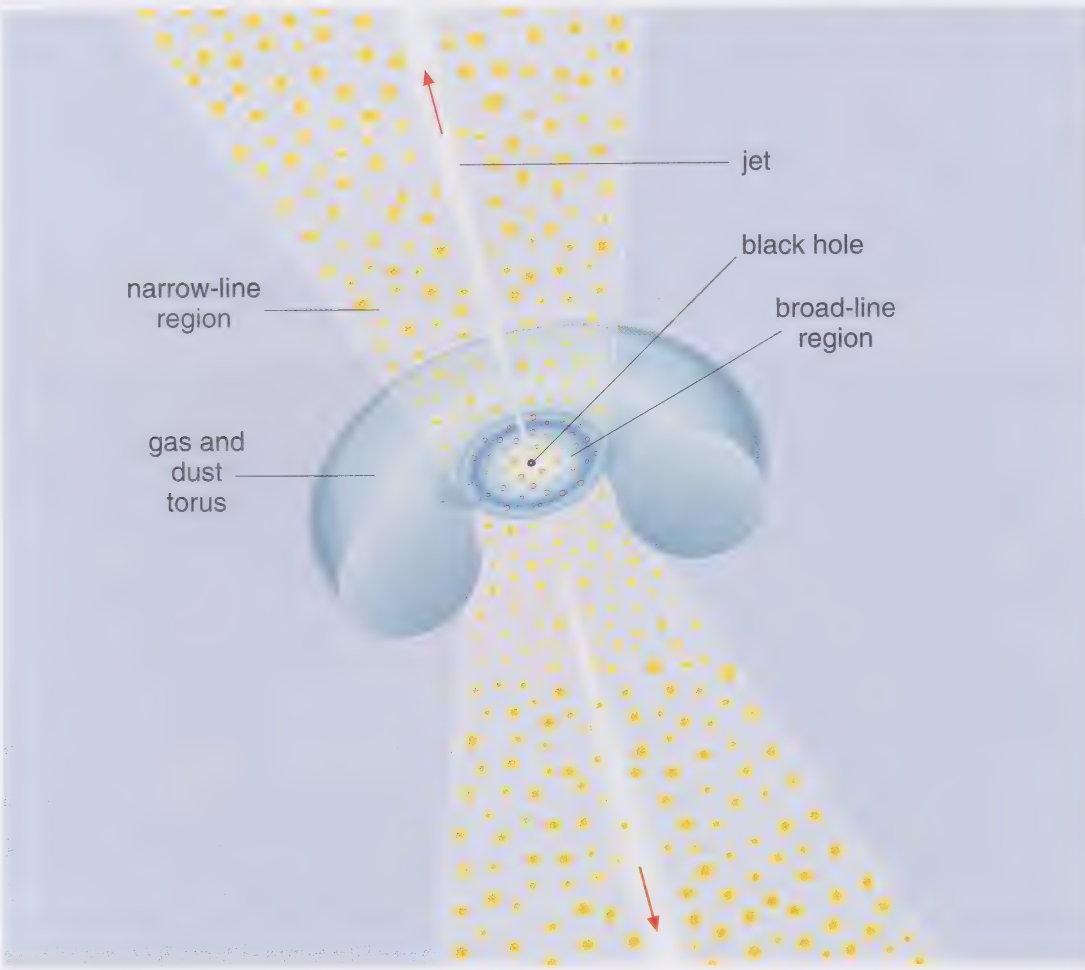


Figure 7.7 A model of an active galaxy. Orbiting gas clouds at different distances from the black hole account for the broad and narrow lines seen in the spectra of many active galaxies.

or merger that is much rarer now than it used to be? Or did the many galaxies with massive black holes at their centres spend part of their lives as a quasar, but eventually cease to be active, possibly because the central black hole consumed all the available matter in its vicinity and effectively ran out of fuel? The Milky Way is certainly not an active galaxy, but it does have a massive black hole at its centre: could it once have been a quasar?

7.4 Clusters of galaxies

Galaxies are not just scattered randomly throughout space. By measuring distances to galaxies, astronomers have shown that they are gathered together in **groups** and **clusters** of varying degrees of richness. The 40 or so galaxies closest to the Milky Way form a sparse cluster, known as the **Local Group**, which has a diameter of about 7 million light years. The Milky Way is one of the largest galaxies in the Local Group, many of the others are dwarf galaxies, quite a few of them satellite galaxies of the Milky Way, or of the great spiral galaxy M31, in Andromeda. Beyond the Local Group are many other sparse clusters, but about 60 million light years away, in the direction of the constellation of Virgo, lies the rich Virgo cluster with about a thousand members, including some large elliptical galaxies.

Studies of the distribution of clusters of galaxies provide clear evidence that the clusters are themselves clustered to form even larger gatherings called **superclusters**. The Local Group is an outlying member of one of these clusters of clusters, called the **Local Supercluster**, although it is sometimes referred to as the Virgo Supercluster, since it is centred on the rich cluster in Virgo. Many other superclusters seem to have a similar structure, consisting of one or two rich clusters together with many sparser clusters. Figure 7.8 shows the results of a very large-scale survey made using infrared-sensitive telescopes. The results show an arrangement of superclusters that is rather like a giant sponge.

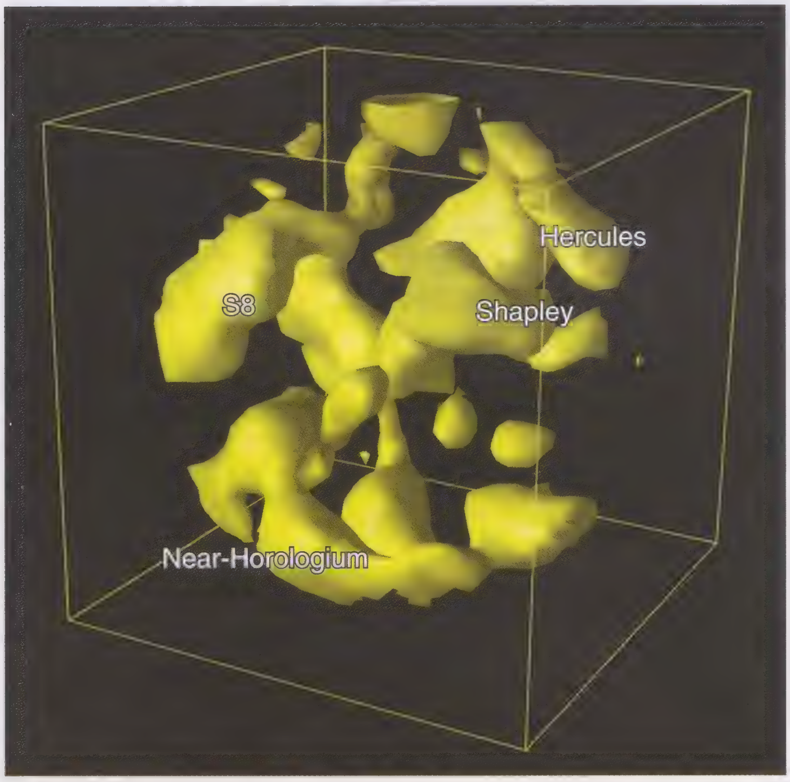


Figure 7.8 Three-dimensional 'density' contours of the galaxy distribution in a sphere of radius 600 million light years centred on the Milky Way. The largest structures visible here are superclusters. This figure was constructed by E. Branchini, C. S. Frenk and L. Teodoro at Durham University from data in the PSCz survey. The survey is a collaboration involving researchers at Cambridge, Durham, Edinburgh, London (Imperial College) and Oxford Universities.

Superclusters seem to be the biggest entities in the Universe. There is no real sign of any clustering of superclusters, although the superclusters themselves can be flattened and even drawn out into filaments. There are spaces between the superclusters that are largely devoid of luminous matter and are usually referred to as **voids**. Thus, on the largest observable size scales, the distribution of matter in the Universe is currently best described as a distribution of superclusters and voids, with the superclusters having typical diameters of a few hundred million light years. The most distant galaxies that can be observed were about 6 billion light years away when their light started its journey towards us. Those galaxies were moving away from Earth at that time and are now believed to be at distances of about 40 billion light years. If we adopt the latter figure as roughly representing the current diameter of the visible Universe, we can say that there is room for a few million superclusters and voids in the visible Universe, and that each supercluster therefore represents about one tenth of a millionth of the volume of the observable Universe.

The way in which galaxies are distributed in space probably reflects how they were formed in the early Universe. To test their theories about this, astronomers use computer simulations. The simulations are primarily concerned with the way in which dark matter can be expected to clump together over time. Luminous matter, or matter capable of becoming luminous, is generally only a minor ingredient in these simulations and can be expected to find its own way to the centres of concentrations of dark matter in response to their gravitational attraction. Figure 7.9 shows various stages in one of these dark matter based simulations of the formation of structure. It gives a fairly good imitation of the real distribution of galaxies.

Now consult the section of the S194 Image Bank devoted to 'clusters of galaxies', where you will find further information including the results of some recent large-scale surveys.

7.5 Chapter summary

The essential points of Chapter 7 are as follows.

1. The Sun is one of about 10^{11} stars that make up the Milky Way galaxy. The Sun is part of a disc of stars, 100 000 light years in diameter, with a bar-shaped bulge at its centre. This is embedded in an extensive stellar halo. However, all these visible components of the Milky Way are believed to be dominated by an even more extensive halo of dark matter that accounts for the great majority of the Milky Way's mass.
2. Most galaxies can be classed as elliptical, lenticular, spiral or irregular, according to their observed shape.
3. The distances of galaxies can sometimes be gauged from their angular sizes.
4. The Doppler effect can be used to measure the movements within galaxies. The discs of spiral and lenticular galaxies show orderly rotation. Elliptical galaxies show little or no overall rotation.

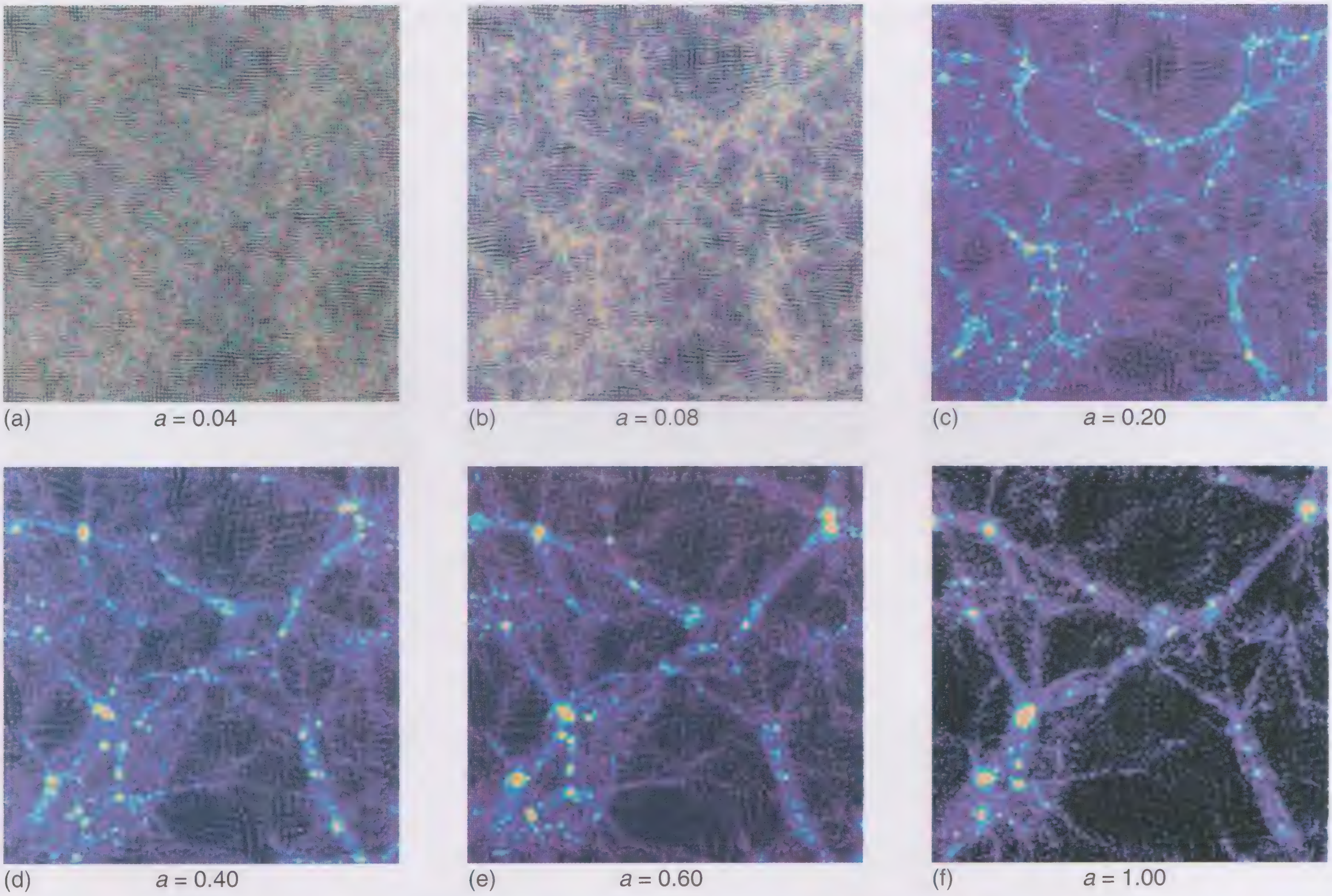


Figure 7.9 A sequence of steps in a simulation of the formation of structure in the Universe, based on the gravitational clustering of dark matter. The values of 'a' indicate the physical size of the simulated region relative to the size of the last frame.

5 Active galaxies emit far more electromagnetic radiation than can be accounted for by their stars and ISM alone. They are believed to contain supermassive black holes. The behaviour of material falling into those black holes is primarily responsible for the additional radiation emitted by active galaxies, and for its variability.

6 Galaxies are gathered together in space in clusters and superclusters. The superclusters are separated by voids, giving rise to a large-scale structure that is similar to that of a sponge. Superclusters are hundreds of millions of light years across. Each supercluster therefore occupies a small but significant fraction of the volume of the visible Universe.

7.6 End-of-chapter questions

Question 7.1 Figure 7.10 shows three galaxies. On the basis of its appearance, classify each one as spiral, elliptical or irregular. ◀

(a) (b) (c)

Figure 7.10 Photographs of galaxies for Question 7.1.

Question 7.2 Using information from the Image Bank or elsewhere, list the following in increasing order of size (actual size not angular size): the Milky Way; the Local Group; the Solar System; the active galaxy Centaurus A; the star cluster M13. ◀

Question 7.3 Suppose that there are two very similar galaxies, one lying three times further from the Earth than the other. Describe as fully as possible the ways in which the galaxies will appear different when viewed from the Earth. ◀

The Universe

8

8.1 Introduction

This book ends by considering the whole Universe, starting with the movement of galaxies, which gives a clue to how the Universe began.

Developing your writing skills

All scientists need the ability to communicate clearly, especially through their writing. Developing good writing skills, particularly when they don't come naturally, takes considerable time and effort but it is essential to develop them. This course alone cannot help you achieve this, but you can use the course materials to improve your writing skills. Much of this chapter is descriptive; it deals in a simple way with matters that are very complicated and far-reaching. Many of its assertions are accompanied by phrases that limit the circumstances to which they apply, or even indicate that there are doubts about their validity. As you read this chapter, look out for these phrases. Ask yourself what is really being said and whether it could be said more briefly. Would a briefer statement mean a vital condition or reservation is omitted? Would a briefer statement be clearer?

When a new **bold** term is introduced, its essential features are usually included in a concise glossary definition. Compare the explanation of the term in the main text with the definition in the Glossary. Ask yourself what has been omitted from the glossary definition, and why. Was the trade-off between brevity and clarity a good one, or could it have been improved?

At the end of every few paragraphs, possibly at the end of every paragraph, stop and ask yourself whether you could summarise what you have just read. If not, try reading it again. Also remember that, important as writing is, it is not the only way of communicating scientific information. Always watch out for places where information might be better presented as a picture, table or chart rather than a block of prose. Part of the skill of good writing is knowing when to stop.

You will be given some chances to practise these skills in the end-of-chapter questions, but you should consciously try to develop them in everything you do.

8.2 The expanding Universe

Chapter 7 pointed out that the spectra of distant galaxies invariably exhibit redshift, showing that those galaxies are receding. In the 1920s, the American astronomer Edwin Hubble measured the distances of some of those galaxies and found that, in each case, the galaxy's distance was approximately proportional to

its redshift. This proportional relationship between redshift and distance is now known as **Hubble's law** and is illustrated in Figure 8.1.

- On the basis of Hubble's law, would you expect the spectrum of Pluto to show a greater redshift than the spectrum of Mars?
- No, Hubble's law relates to distant galaxies, it has nothing to do with planets or stars. It does not even apply to nearby galaxies, some of which are approaching the Milky Way.

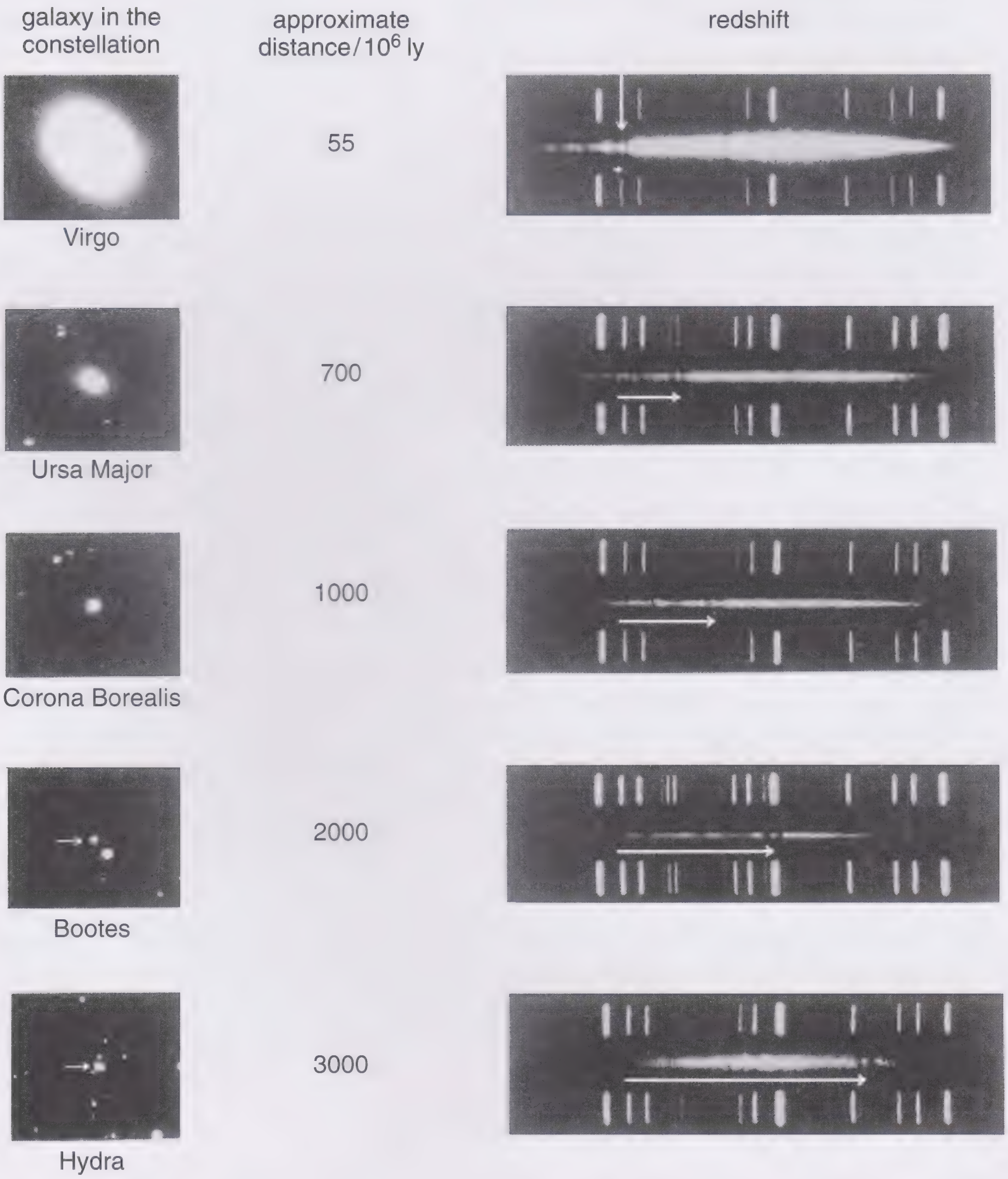


Figure 8.1 Hubble's law: the column on the left shows five galaxies together with their respective distances. The column on the right shows the visible spectrum of each galaxy, with blue to the left and red to the right. (The lines above and below each spectrum are reference lines added in the observatory.) The redshift of each spectrum is shown by the arrow under that spectrum. The redshift increases with the distance of the galaxy.

There are two important implications of Hubble's law

1 The approximate distance of a far-off galaxy can be deduced from a relatively simple measurement of its redshift. Since galaxy distances are generally rather difficult to measure by other means, this redshift-based technique has become the standard method of determining distance and provides the basis for the large-scale surveys of galaxy clustering that were mentioned in Chapter 7.

2 The systematic increase of redshift (and consequently recession speed) with distance from the observer indicates that the Universe is in a state of overall expansion, at least on the large scale.

Hubble's discovery of the large-scale expansion of the Universe must surely count as one of the greatest discoveries of all time (Figure 8.2). Even so, it is important not to misconstrue its meaning. First, it is a discovery that applies only on the *large scale*. While it is true that superclusters of galaxies are, on average, moving further apart, individual clusters are not necessarily expanding, and it is certainly not the case that individual planets, stars or galaxies are expanding. Individual stars and planets are held together by relatively strong forces that easily resist the rather weak tendency towards overall expansion. Second, even though distant galaxies are moving away, it does not follow that Earth is located at the unique centre-point of the expansion. Rather, astronomers believe that the expansion is *uniform* in nature, implying that it would appear the same to any observer located in any galaxy. In this sense, the expansion has no centre or, if you prefer, any point can equally well be regarded as the centre of the expansion. There is no 'preferred' point anywhere in the Universe. The next activity will give you an idea of how this is possible.

Figure 8.2 Edwin Hubble (1889–1953), the first astronomer to establish definitely that there are other galaxies beyond the Milky Way, and the first to provide a useful scheme for classifying galaxies. His greatest discovery, however, was the relationship between redshift and distance and, by implication, cosmic expansion.

Activity 8.1 Modelling the expanding Universe

20 minutes

For this activity you need a wide elastic band, a pen and a ruler.

Draw some dots on the elastic band, a few centimetres apart (no need to be exact). These represent galaxies at one moment in the history of the Universe.

Choose one dot to be the Milky Way. Measure the distance from 'the Milky Way' to each of the other 'galaxies'.

Stretch the elastic band as shown in Figure 8.3. The dots now represent galaxies at some later time in the history of the Universe. Hold the elastic band next to the ruler and roughly measure the distance of each galaxy from the 'Milky Way'. You will find that the galaxies that were furthest away to start with have moved through the greatest distance during the stretching – in other words, they have moved the fastest.

Repeat with a different galaxy representing the Milky Way. You will get the same result. ◀

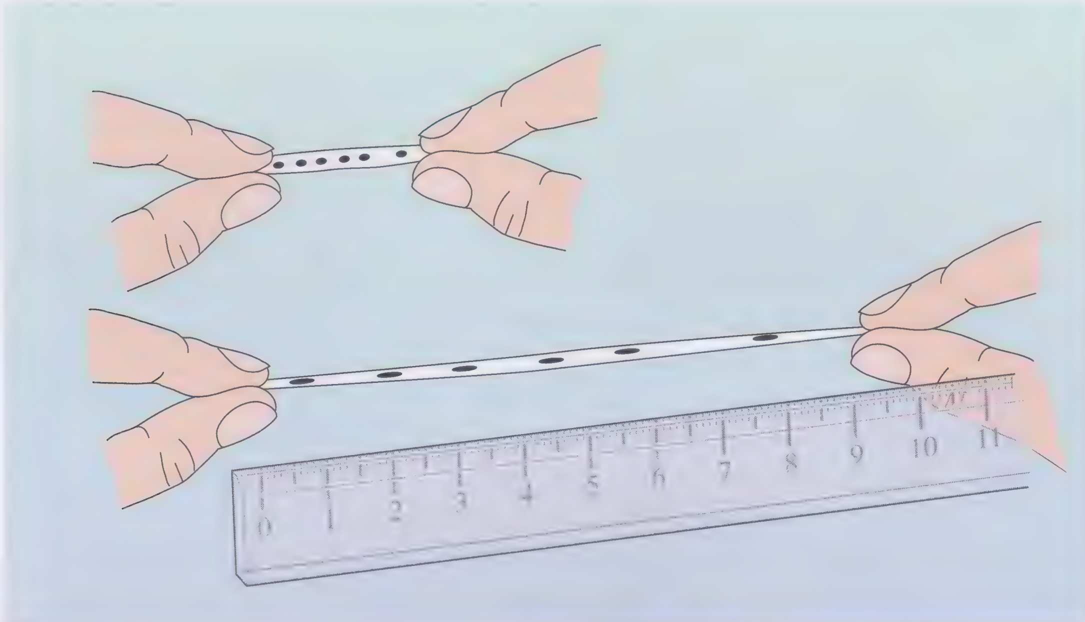


Figure 8.3 Modelling galaxies in a uniformly expanding universe.

Activity 8.1 suggests that, whichever galaxy we lived in, we would always see the other galaxies as moving away. You can easily imagine using a square elastic sheet to demonstrate the same effect in two dimensions or, with a little more effort, an elastic cube in three dimensions. (If you can't imagine an elastic cube, think of the raisins in an expanding fruit cake as it bakes in an oven.) No galaxy can be said to lie at the centre of a uniformly expanding Universe – such a Universe has no centre.

When you first hear that the Universe is expanding it is easy to imagine that the distant galaxies might all be moving through space as though ejected from the site of some great explosion. Indeed, many people have the mistaken impression that this is exactly what happened; that the explosion was the **big bang** and that we can find the one place in space where it occurred by simply tracking the galaxies backwards and seeing where they would have met together. However, as emphasised above, any observer attempting to do this, from any galaxy, would find themselves at the 'centre' of the expansion. Clearly, this is inconsistent with the picture of a simple explosion; we need a better way of thinking about the expansion and the big bang that initiated it.

The elastic band you used in Activity 8.1 was only intended to provide a model of the expanding Universe, yet it might be a better model than you think. Scientists base their ideas about the expansion of the Universe and the big bang

on Albert Einstein's theory of **general relativity**. This highly mathematical theory, which dates from 1916, is well beyond the scope of this course, but the following can be said about it. General relativity gives scientists the means of describing space and time mathematically. Within these descriptions, space behaves something like an elastic block; it becomes meaningful to speak of space as being curved, or even to talk of it as expanding.

To scientists, the recession of distant galaxies is primarily attributable to the expansion of space. Rather than travelling *through* space, galaxies are carried along by the expansion *of* space, just like the dots you drew on the elastic band. In this sense, galaxies are simply visible markers that help us to observe the expansion of space. If you adopt this view of the expansion, it becomes much easier to make sense of a uniform expansion that has no preferred centre. The big bang was not an explosion that hurled matter out into previously empty space; rather it marked the beginning of a uniform cosmic expansion that created the space we now observe.

This 'elastic' view of the expanding Universe also accounts for Hubble's law (Figure 8.4). Imagine light of a particular wavelength being emitted from a distant galaxy and travelling towards the Earth. As that light travels through space, its wavelength is influenced by the continuing expansion of space. As a result, by the time the light reaches the Earth its wavelength has increased and the light has been redshifted. The more remote the galaxy that emitted the light, the longer the light has been travelling through expanding space, and the greater its redshift when finally observed on Earth.

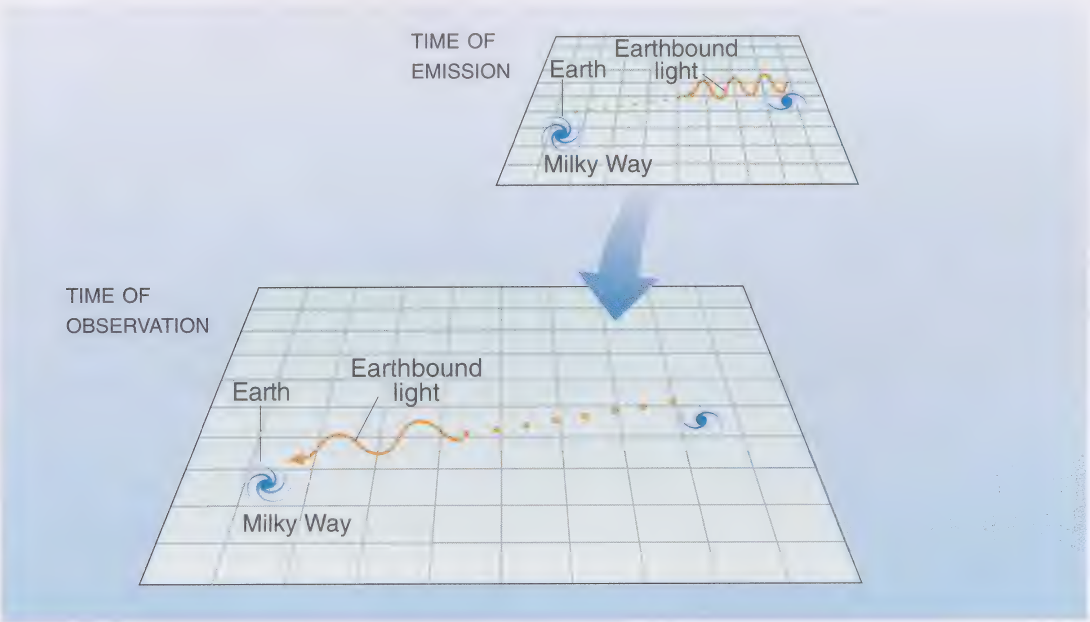


Figure 8.4 Expanding space accounts for Hubble's law: the longer light spends travelling through space, the greater is its observed redshift.

8.3 Distance, redshift and recession speed

According to the 'expanding space' explanation (really the *general relativistic explanation*), the observed redshifts of distant galaxies are *not* the result of the Doppler effect. None the less, the expanding space approach supports the view that the greater the distance of a galaxy, the greater its speed of recession. You saw this in Activity 8.1: the galaxies furthest from the simulated Milky Way

receded most rapidly. If one galaxy lies at twice the distance of another, it has twice the recession speed.

Of course, when we observe real galaxies we do not see them as they are now but, rather, as they were when their light left them. This complicates the relationship between observed distances, redshifts and recession speeds. Establishing the exact connection between those quantities is an ongoing challenge for astronomers. It requires accurate and reliable measurements of the distances to remote galaxies, independently of their redshifts.

- Outline two methods, which you have met in this course, that astronomers can use to measure distances (without using redshifts).
- One way is to apply the 'far means faint' idea which you met earlier (in Chapter 4). If two objects are identical, the further one appears fainter by an amount that depends on the square of its distance relative to the closer object. Another method is to use angular sizes, as indicated in Chapters 2 and 7. If two identical objects are at different distances, the angular size of the more distant one is smaller by an amount that depends on its distance relative to the closer one.

- Why will there be problems applying these methods to distant galaxies?
- Both methods rely on comparing identical objects. When observing a very distant galaxy, it is difficult to know whether it is identical (or even similar) to a nearby one. Also, even if we can say that one galaxy is, for example, ten times more distant than another, if the distance of the closer galaxy is not known exactly, the distance to the further one is also uncertain.

Using either apparent brightness or angular size to deduce distance involves making assumptions about the nature of very distant objects, which may or may not be reliable – but astronomers have to use what is available, and most methods for finding distance essentially use either size or brightness. In the decades since Hubble's work, the details of the methods of distance measurements, the assumptions that underlie them, the types of objects studied and the instruments used in the observations have been developed and refined. However, measuring astronomical distance is still an area fraught with difficulty.

- Since the mid 1990s a kind of supernova called a type Ia supernova has played an important part in determining galaxy distances. Why is it reasonable to choose supernovae as distance indicators? What problems might their use present?
- Supernovae are intrinsically exceedingly bright so, although they are relatively rare, they are highly prominent and can be seen even in very distant galaxies. The problems associated with their use include the need to ensure that those being compared really are similar (this is why a particular type of supernova is chosen), and the concern that remote supernovae, which exploded very long ago, might be somewhat different from their modern counterparts because of evolutionary effects in stars and/or galaxies.

Despite all the difficulties, astronomers believe they have been increasingly successful in pinning down the relationship between distance, redshift and recession speed. The key quantity in that relationship is known as **Hubble's constant**. This is usually denoted H_0, and provides a measure of the *current* rate of expansion of the Universe. The word 'current' is used to account for the possibility that the rate of expansion might have been greater or lesser in the past. In a uniformly expanding Universe, the rate of expansion must be the same at every place at any given time, but it does not have to be the same at all times.

The best available determinations of Hubble's constant (which have about a 10% uncertainty) imply that the average recession speed of distant galaxies currently increases by about 22 kilometres per second for every additional million light years from the Earth (or from any other starting point). Rather surprisingly, measurements (including those based on supernovae that were mentioned above) also indicate that the rate of expansion is increasing, implying that the cosmic expansion is accelerating. The next section considers what might be causing that.

Activity 8.2 Speed and distance

10 minutes

Estimate the current distance of a galaxy that has a recession speed of 1000 kilometres per second, assuming that its recession speed is entirely caused by the expansion of the Universe.

How safe do you think it is to assume that the recession of this galaxy is entirely caused by cosmic expansion? Describe another factor that might affect its recession speed.

Would you be more or less confident when making this assumption about galaxies with recession speeds of 100 kilometres per second or 10 000 kilometres per second? ◀

8.4 The early Universe

Imagining the expansion of the Universe in reverse and tracking galaxies backwards does not lead to a unique point in space, but it does give us a crude estimate of when the expansion began. This approach indicates that the big bang occurred about 15 billion years ago. More sophisticated techniques allow a more precise estimate of about 13.7 billion years.

In the early Universe, conditions would have been very different from those prevailing now. Early on, when everything was more compressed than it is now, the average density of matter would have been higher and so would the temperature. Very early on, it would have been too hot for stars or galaxies to exist and, extremely early on, too hot even for atoms or nuclei to exist.

The history of the Universe is believed to involve continuous expansion and cooling, as indicated in Figure 8.5 (overleaf). The Universe may have been at its simplest in the very earliest times. As it cooled, different structures emerged and the Universe became more complicated. There are many uncertainties about the early evolution of the Universe but the general view is that the particles (protons and neutrons) of which atomic nuclei are composed first formed when the Universe had been expanding for about one hundredth of a thousandth of a

second. It didn't become cool enough for those particles to start forming nuclei until the Universe was a few minutes old. However, the process of nucleus building ended about 30 minutes later, by which time hydrogen and helium were already established as the most common nuclei. (The ability to predict the right relative abundances of light nuclei is regarded as one of the greatest successes of the big bang theory.)

About 400 000 years passed before it was cool enough for atoms to form. This was a key event, because it marked the transition from an opaque Universe, in which radiation could travel only a tiny distance before being scattered, to a transparent Universe, in which radiation could travel relatively freely.

Once the Universe became transparent, matter and radiation are generally supposed to have followed rather separate lines of development. The matter, including hydrogen and helium, but mainly a far greater amount of dark matter,

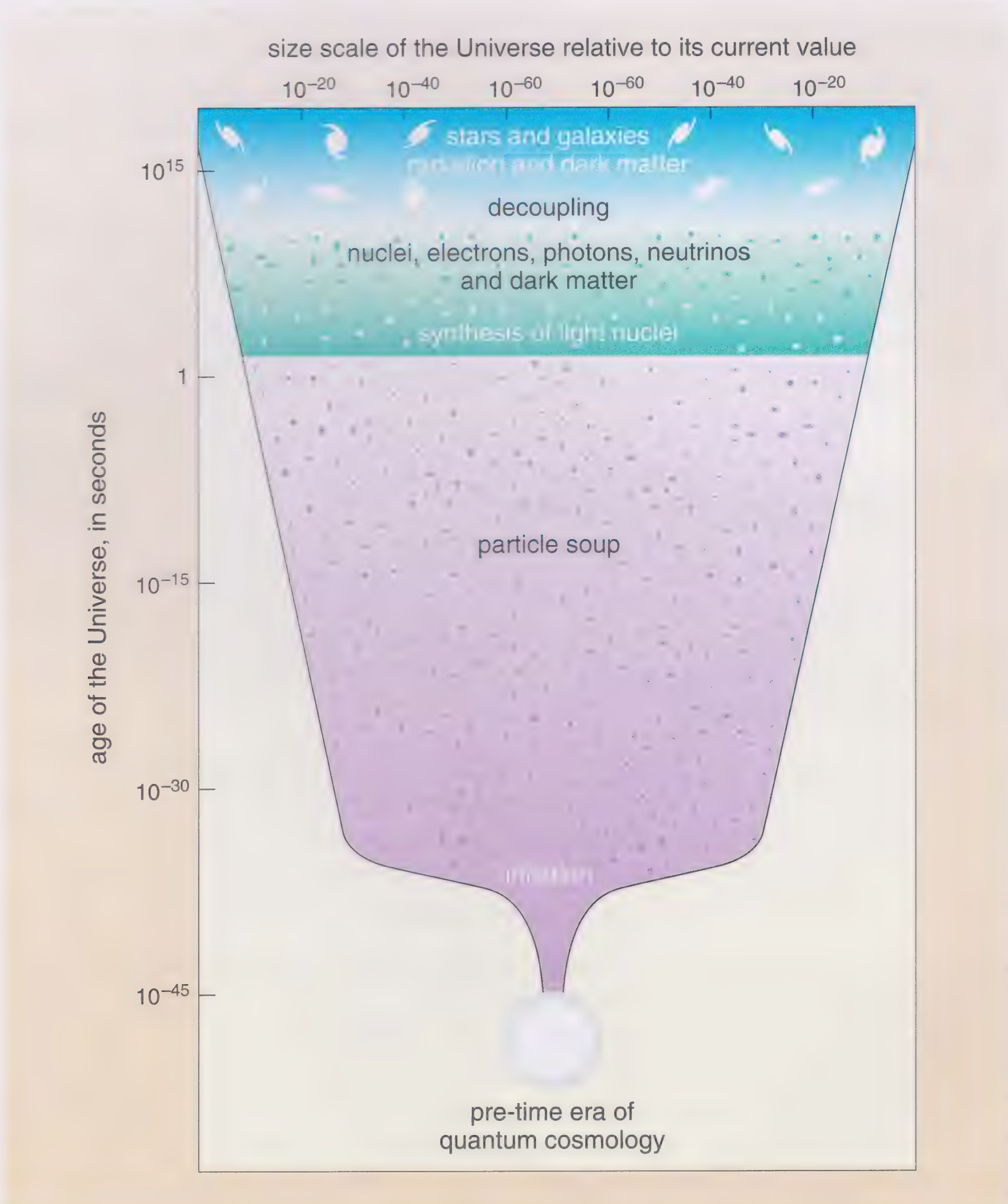


Figure 8.5 The history of the Universe as it expands and cools. At the time of decoupling, the size scale of the Universe was about 10^{-3} of its current value.

expanded and cooled patchily. In regions destined to become superclusters, the dark matter became relatively more concentrated and drew in the hydrogen and helium that would eventually form stars and galaxies. Other regions became relatively empty and eventually produced the voids we see today.

The large amount of radiation released when the Universe became transparent has also been expanding and cooling since then. The average temperature when the radiation was released was about 3000 °C, so the radiation would have been mainly the kind of orange-red light that is predominantly emitted at that temperature. Since that primordial radiation was emitted it has been travelling through space. However, cosmic expansion has caused typical points in space to increase their separation by a factor of one thousand or so during that time. As a result, the wavelength of the primordial radiation has also increased by a factor of about one thousand, transforming it into microwave radiation. This microwave radiation accounts for most of the radiant energy in the Universe. It was first detected in the 1960s, and has since been the subject of intensive research, from the ground, from balloons and from spacecraft. Since the radiation is a consequence of uniform cosmic expansion, it comes almost equally from all directions in space and consequently is called **cosmic microwave background radiation** (CMB).

The CMB is highly uniform but there are very slight differences in the intensity of radiation from different parts of the sky. These tiny departures from uniformity are shown in Figure 8.6. They are a direct consequence of conditions in the early Universe. They give us a fairly direct view of the Universe as it was about 400 000 years after the big bang, including some indication of the relatively dense regions that will develop into superclusters rather than voids. Such images are referred to as the 'Universe's baby pictures', and the CMB has been called the 'afterglow' or even the 'echo' of the big bang. By studying this radiation, scientists have made their best estimates of the time since the big bang, the total density of matter in the Universe, and the fraction of matter that is dark rather than luminous.

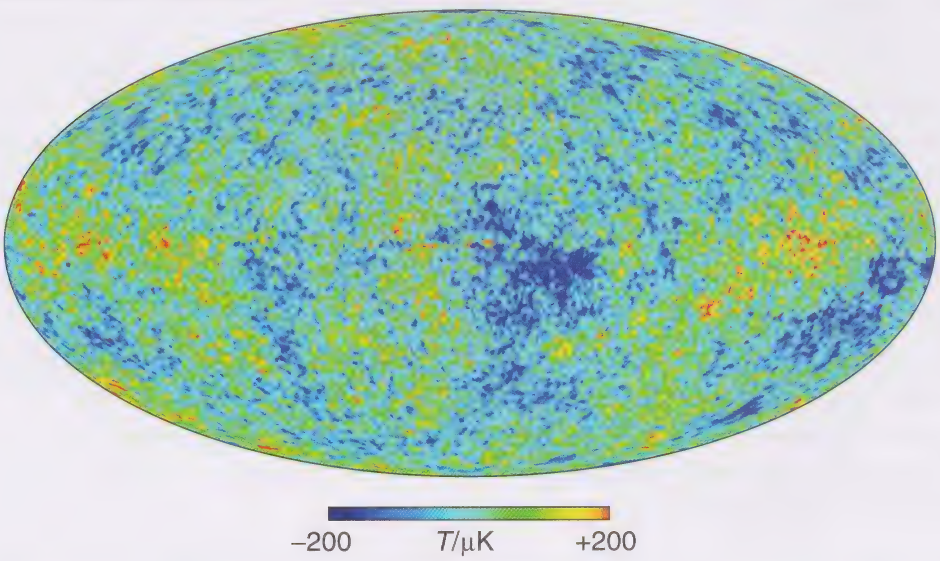


Figure 8.6 The Universe's baby picture: a false colour image of the whole sky recorded using cosmic microwave background radiation. This is the expanded, cooled and redshifted remnant of the visible radiation that was emitted when the Universe became transparent, about 400 000 years after the big bang.

Studies of the CMB have also revealed another enigmatic feature of the Universe – a feature already suggested by studies of supernovae in distant galaxies. The Universe contains something called **dark energy**. The origin and nature of this dark energy is a deep mystery. Despite its name, it is not thought to be connected with dark matter, nor with cosmic background radiation, nor any other known kind of matter or radiation. It may be associated with a quantity called the **cosmological constant** which Einstein introduced in the context of general relativity, but even that is far from certain. Whatever the source of the dark energy, its effect is to accelerate the expansion of the Universe (this is what the supernova studies first revealed). Until about one billion years ago, the effect of the dark energy was overwhelmed by the effect of matter and radiation, which both tend to slow the cosmic expansion. However, the expansion of the Universe has continuously reduced the average density of matter and radiation, while apparently leaving the dark energy unchanged. Dark energy is now believed to account for about 70% of the energy in the Universe, matter for about 30%, and radiation for a small fraction of 1%. Consequently, the dark energy has now become the dominant influence on cosmic expansion, which is speeding up as a result. Much remains to be done to confirm these recent findings, and even more if they are to be understood. None the less, dark energy is an excellent example of the way in which the Universe can still surprise and puzzle astronomers as well as inspire them with awe and wonder.

Now consult the section of the S194 Image Bank devoted to 'the Universe', which gives additional information about several of the issues discussed in this chapter. Pay particular attention to references to the cosmic microwave background radiation, since this is one of the most important sources of information about the Universe. The Data Bank has references to websites that will help you keep abreast of developments in this field.

8.5 Chapter summary

The essential points of Chapter 8 are as follows.

1 Hubble's law describes a proportional relationship between redshift and distance for remote galaxies. Its discovery provided a simple means of determining the distances of galaxies, and evidence of the uniform expansion of the Universe on a large scale.

2 The modern view of cosmic expansion is that it involves the expansion of space in a way described by general relativity. This approach provides a natural explanation of Hubble's law.

3 Hubble's law may also be expressed in terms of a proportional relationship between the current distance of a galaxy and its current recession speed. Recent measurements of Hubble's constant indicate that galaxy recession speeds currently increase by about 22 kilometres per second per million light years, with an uncertainty of about 10%.

4 Evidence indicates that the expansion of the Universe began about 13.7 billion years ago in an event known as the big bang.

5 As the Universe expanded and cooled, the nuclei of light elements were formed with predictable abundances. Later the Universe became transparent, releasing the radiation that became the observed cosmic microwave background radiation.

6 Departures from uniformity in the cosmic microwave background radiation are related to the formation of superclusters and voids. They provide detailed information about the age and composition of the Universe, and confirm the presence of the little understood dark energy that is thought to account for most of the energy in the Universe.

8.6 End-of-chapter questions

Question 8.1 A certain galaxy is found, from the redshift of its spectrum, to be receding at 9600 km per second. Using what you have learned in this chapter, estimate the distance to the galaxy in light years. Assuming that the value of Hubble's constant is the biggest source of uncertainty, what is the uncertainty in your answer? ◀

Question 8.2 Suppose that you are talking to a friend who has heard of the big bang but reckons it is 'only a theory, with no basis in fact'. How would you counter such a claim? ◀

Question 8.3 Look at the glossary definitions of Hubble's constant and Hubble's law. Which important items of information omitted from either definition were included in the main text? ◀

Question 8.4 Write a concise summary of the 'elastic space' view of cosmic expansion. ◀

Question 8.5 If you were asked to rewrite Chapter 8, at which points would you consider replacing part of the text by a diagram or some other means of representing information? ◀

9 Summing up

9.1 End-of-course questions

Each question in this section covers material from more than one chapter. These questions will help you further develop your understanding of the course and help you to prepare for the End-of-Course Assessment, which also includes questions that cover more than one chapter.

Question 9.1 How much bigger is the diameter of the Sun than the thickness of its photosphere? Express your answer in both scientific and ordinary notation. ◀

Question 9.2 In the early seventeenth century, the astronomer Galileo Galilei (1564–1642) observed Venus through a telescope. He found that, like the Moon, Venus went through phases from crescent to full and that, as its phase changed, so did its angular size, as shown in Figure 9.1. With the aid of a sketch, explain how the motion of Earth and Venus around the Sun can account for how the appearance of Venus changes. ◀

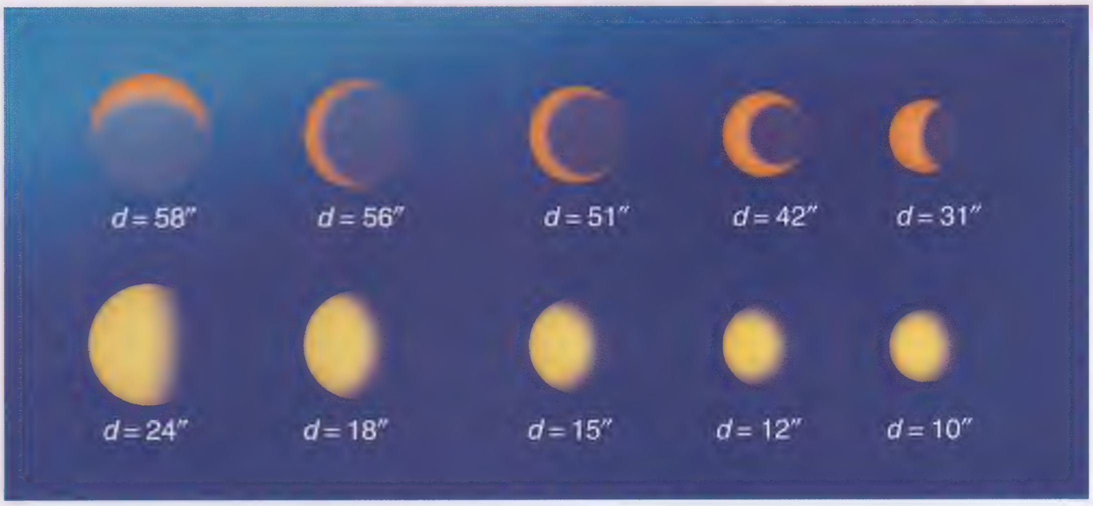


Figure 9.1 The changing appearance of Venus (drawings based on modern photographs). Note that the top row of images is on a different scale from the bottom row. Also note the angular diameters, d.

Question 9.3 The planet Venus is sometimes referred to as the 'morning star' or the 'evening star'. With reference to your sketch for Question 9.2, explain why Venus can only be observed close to sunrise or sunset (and never at midnight) and say roughly whereabouts in the sky you would expect to see it. ◀

Question 9.4 In searching for exoplanets which may support life, astronomers look for evidence of rocky planets orbiting other stars. Explain why planets containing a large proportion of icy materials are unlikely to provide suitable conditions for the evolution of living organisms. ◀

Question 9.5 Some galaxies are called 'starburst galaxies' because they seem to be undergoing an enormous burst of star formation. Such galaxies are powerful sources of infrared radiation. Write a few sentences to describe what must be happening in the ISM of such galaxies, and explain why this gives rise to infrared emission. ◀

Question 9.6 Galaxies and quasars with large redshifts do not necessarily appear redder than those that are closer to Earth. Suggest a reason for this. ◀

Question 9.7 A friend has just been to a talk on astronomy, and says: 'I'm confused. The lecturer told us that the individual stars we can see making up constellations are relatively close and are all in our Milky Way galaxy. Then the lecturer talked about other galaxies which are much further away and contain billions of stars. But then the lecturer went on to talk about other galaxies being in constellations like Andromeda. That doesn't seem to make sense.'

What would you say to sort out your friend's confusion? ◀

Question 9.8 The background radiation is brightest at a wavelength of about 1 mm (i.e. it consists mainly of microwaves). In the distant future, when the Universe has expanded and cooled considerably, how will the background radiation differ from that observed today? ◀

Question 9.9 An astronomer observes two elliptical galaxies, whose overall shape and colour indicate that they are very similar. One has an angular size of 2 arcmin and a recession speed of 1320 km per second. The other has an angular size of 30 arcsec and appears to be a little less than one-fifteenth as bright as the other. Deduce the distance to the fainter galaxy. Express your answer in light years and in kilometres. ◀

9.2 The end of the course: what next?

Now that you have completed this course, you have experienced an overview of most areas of astronomy. We hope you enjoyed it and found it interesting. In this short course, we have had to leave many questions unanswered, for example:

- Why are the giant planets so similar to one another yet so different from the terrestrial planets?
- How did the Earth acquire its life-supporting atmosphere?
- Which nuclear reactions take place inside stars?
- Why do some stars explode when they have exhausted their nuclear fuel?
- How do some galaxies acquire a spiral structure?
- Will the Universe keep expanding for ever?

If you are intrigued by such questions, you would probably like to learn more about astronomy and perhaps other areas of science. There are several Open University courses that might interest you, details of which are in the Study Guide.

The course team wish you good luck in your future studies.

Questions: answers and comments

Our comments are in curly brackets { }. You are not expected to have included that information in your answers.

Question 2.1 The range is from about 1 m down to a little less than 0.001 m. {The short end of the range lies just over three marks to the left of the 1 m mark in Figure 1.3, i.e. a little shorter than 0.001 m.}

Question 2.2 Energy released by nuclear reactions in the Sun's core is initially carried away by radiation. Although repeatedly absorbed and re-emitted, it is radiation that carries the energy through the radiative zone. It is absorbed at the bottom of the convective zone, where it causes the convective flows that are largely responsible for transporting energy up to the photosphere. Radiation takes over again in the photosphere; the radiation emitted there escapes from the Sun and may transport energy to the Earth's surface where it can be absorbed.

Question 2.3 Conventional fuels could maintain the Sun's output of light and heat for only a few thousand years, which is not nearly long enough to sustain the evolution of life on Earth over the millions of years deduced from fossil records. Nuclear reactions produce *much* more energy output for a given amount of fuel, enabling the Sun to emit a steady output over thousands of millions of years.

Question 2.4 There are two methods for answering this question.

Method 1

The expression given is:

actual size = (angular size in degrees × distance) ÷ 57.

This can be rewritten as:

diameter of Sun = (angular size of Sun in degrees × distance of Sun) ÷ 57.

The angular size of the Sun is about the same as that of the Moon, i.e. 0.5°, so:

diameter of Sun = (0.5 × 150 million km) ÷ 57
= 1.32 million km.

Method 2

The Sun's diameter is about 400 times the diameter of the Moon. Therefore, if the Moon is 3476 km in diameter, the Sun must have a diameter of about 400 × 3476 km = 1.39 million km. {This is not as accurate as in Method 1, because Chapter 2 states that the diameter of the Sun is *about* 400 times the diameter of the Moon.}

Question 2.5 (a) There are 60 arcmin in one degree (1°), so the Sun's angular size is 30 arcmin. The angular size of the sunspot is:

30 arcmin ÷ 20 = 1.5 arcmin.

(b) One arcmin is 60 arcsec, so 1.5 arcmin = 90 arcsec.

Question 3.1

150 million km = 150 000 000 km

= 150 000 000 000 m = 1.5 × 100 000 000 000 m
= 1.5×10^{11} m.

Question 3.2 See Figure 3.16.

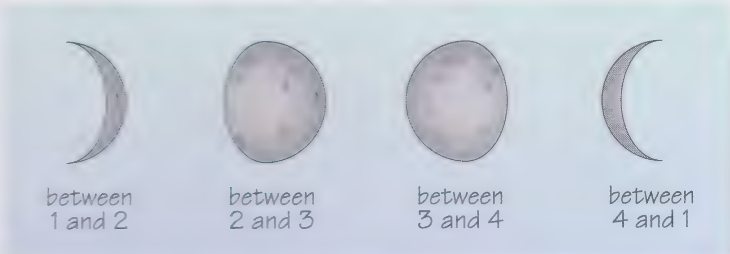


Figure 3.16 Answer to Question 3.2.

{When the Moon is less than half-full it is called a crescent. When it is between half-full and full it is called gibbous. The Moon is said to be 'young' between new and first quarter, and 'old' between third quarter and new. It is said to be 'waxing' between new and full, and 'waning' between full and new.}

Question 3.3 The Moon has a far side in the sense that there is a side that does not face the Earth. The Moon does *not* have a dark side: Figure 3.8a shows that every region of it is in sunlight at some time in the lunar orbit.

Question 3.4 Solar eclipses occur when the Moon lies between the Earth and the Sun, whereas lunar eclipses occur when the Earth lies between the Moon and the Sun, as shown in Figure 3.10. The probability of a perfect alignment in either case is rare because of the tilt of the Moon's orbit about the Earth. However,

as the Earth's shadow is much larger than the Moon's, the probability of the Moon passing through the Earth's shadow is much greater than that of the Earth passing through the Moon's shadow because the alignment need not be so precise.

Question 3.5 Terrestrial planets are similar in size to the Earth and much smaller than the giant planets; they lie much closer to the Sun than the giants. They have at the most two natural satellites each and no ring systems. They are composed mainly of rocky materials, whereas the giants also contain icy materials but have envelopes of hydrogen and helium.

Question 3.6 Comets must have formed in the outer parts of the Solar System. Low temperatures are required for icy materials to condense into solid grains and come together to form a comet, and such temperatures occur only very far from the Sun.

Question 3.7 The flight path would need to be computed very accurately in order not to miss the target. The gravitational force on the space probe caused by the comet would be weak, so it would be difficult to maintain orbital motion. {The space probe will have to be slowed to a very low speed so that it will go into orbit and not drift off into space.} The gas and dust around the comet could be hazardous to the space probe. {In fact, the lander will be deposited when the comet is sufficiently far from the Sun that it is not very active – this is partly why the flight time is very long.} The lander will have to attach itself to the surface to avoid being launched into space in the very low gravity of the comet and to be able to drill below the surface.

Question 3.8 From the captions and images in the Image Bank, impact craters can be distinguished from volcanic craters: impact crater floors are lower than the ground level around the crater; impact craters can be surrounded by a blanket of ejected material. You may also have noticed that large impact craters often have central peaks from 'rebounded' material.

Question 4.1 Orion is in the southerly sky at midnight on New Year's Day, so it must be in the opposite direction to the Sun (Figure 4.10). Therefore, six months later, when the Earth is on the other side of the Sun, Orion will be in roughly the same direction in the sky as the Sun. {It will therefore be unobservable.} See Figure 4.10.

Figure 4.10 Answer to Question 4.1.

Question 4.2 Figure 4.6 shows that there is a band of stars crossing the region of the Southern Cross. At lower resolution these stars would blend together and appear like the Milky Way. Therefore, it is reasonable to guess that the Milky Way consists of a huge number of stars. {This is correct, as you can see if you have binoculars or a telescope and examine the Milky Way in your night sky.}

Question 4.3 Three of the stars are bluish-white, so they must have similar temperatures, but the one nearest the top of the picture is orange, so it must be significantly cooler. Of the three bluish stars, the one nearest the bottom of the picture is brightest, so it is probably the nearest, while the one on the right is faintest, so it is probably the most distant. {Note that we said 'probably' because we cannot be sure that these three stars are of similar size as well as similar temperatures. Note, too, that we said nothing about the distance of the reddish star because we can only compare like with like.}

Question 4.4 Star A is four times further away than star B, so it will appear to be $4^2 = 4 \times 4 = 16$ times fainter than star B.

Question 4.5 By extending Table 4.2 upwards for two rows, you can see that 0.000 001 metres (one millionth of a metre) is 10^{-6} metres. Extending the table by another six rows to a millionth of a millionth gives 0.000 000 000 001, which is 10^{-12} in scientific notation.

Question 4.6 (i) The distance 34.135 ly has too many significant figures because it is not known to any greater accuracy than 3 ly. It should be written as 34 ± 3 ly. (ii) Both the distance and its uncertainty have too many significant figures. It would be more correctly stated as 29 ± 6 ly. (iii) The uncertainty and the distance are not matched. The uncertainty implies that the distance is known to an accuracy of about one hundredth of a light year, whereas the value is only quoted to an accuracy of one light year. If the distance is precisely six light years then, in this case, it should be quoted as 6.00 ± 0.01 ly.

Question 5.1 Dense cloud; protostar; main sequence star; red giant; white dwarf plus planetary nebula.

Question 5.2 The Trifid Nebula is a site of star formation, where molecular cloud fragments collapse to form protostars and then young stars whose radiation heats the surrounding gas, causing it to glow. The Cat's Eye Nebula is a planetary nebula, i.e. material ejected from the outer parts of a solar-type star after it has exhausted its main fuel supply and become a red giant. It shows evidence of episodic emissions as a series of pulses at 1500-year intervals. The remaining central core of the star becomes a white dwarf. The Crab Nebula is a supernova remnant; the material ejected when a star over 11 times the mass of the Sun was shattered in a tremendous explosion after exhausting its nuclear fuel. In this case, the remaining central core of the star becomes a neutron star (pulsar); another possibility would have been the formation of a black hole.

Question 6.1 To quote Section 6.2.1, 'no other chemical element comes anywhere near carbon in its facility to form the large and complex compounds that are necessary for life'. Life is believed to be based on huge, complex chemical compounds, and silicon is unlikely to form sufficiently huge, complex compounds.

Question 6.2 A considerable increase in solar luminosity will cause an increase in the Earth's surface temperature to the point where it is too hot for liquid water and for huge, complex carbon compounds. The Earth will then be uninhabitable. {The surface of Mars might have a period of being inhabitable. This is because a warmer surface will lead to gases, notably carbon dioxide, being released from the surface, thus increasing the atmospheric pressure to the point where water can exist as a liquid.}

Question 6.3 If Europa no longer orbited Jupiter, it would no longer be tidally heated, and so its oceans would freeze. {It would then resemble many of the other satellites of the outer planets.}

Question 6.4 With no life on Earth there would be no photosynthesis, hence little oxygen, hence little ozone, and so the ozone absorption line would, at most, be very weak. {There would be other changes too, but these are beyond the scope of this course.}

Question 6.5 There are at least three changes that you might have thought of, based on the information given in this course.

1 The peak in the spectrum would be at longer wavelengths.

2 Life would be unlikely on a cold world, so there would be no ozone absorption line.

3 A cold atmosphere would contain little water vapour, so water absorption lines would be weak.

Question 7.1 Galaxy (a) is elliptical. It has a smooth, oval shape and no sign of spiral arms or a central bulge.

Galaxy (b) is spiral. It has a central, bright concentration of light (the bulge) and clear spiral arms.

Galaxy (c) is irregular. It has an irregular shape and irregular distribution of light.

Question 7.2 The smallest is the Solar System, which is very much less than 1 ly across; M13 is next, which lies within the Milky Way and is about 150 ly across; then there is the Milky Way (about 100 000 ly across); then Centaurus A (2.5 million ly); and, finally, the Local Group, which is 6 to 8 million ly across.

Question 7.3 The more distant galaxy will have a smaller angular size and appear fainter. Its angular size will be about one-third that of its nearer counterpart, and its apparent brightness will be one-ninth. {The two galaxies could also be seen in different orientations, e.g. either face-on or obliquely, but we cannot be definite about that.}

Question 8.1 Taking Hubble's constant to be 22 kilometres per second per million light years, and using Hubble's law, we can deduce that a recession speed of 9600 km per second puts the galaxy at a distance of (9600 ÷ 22) million light years, i.e. 436 million light years. Noting that Hubble's constant was only specified to two significant figures, it is inappropriate to treat the final 6 in the answer as meaningful. If the uncertainty in Hubble's constant is 'about 10%', the uncertainty in the derived distance will also be about 10%. Therefore, the answer could be quoted as 440±40 million light years.

Question 8.2 You could describe three key observations that support the idea of the big bang.

1 Galaxies are observed to be moving apart from one another (you might go on to say something about redshift, making the comparison with the sounds from receding vehicles).

2 The success of the big bang in accounting for the relative abundances of various light nuclei.

3 Microwave-sensitive telescopes pick up background radiation that is best interpreted as the expanded (redshifted) remnant of the radiation emitted when the Universe first became transparent. {You could even extend this by talking about the understanding that exists of the non-uniformities in the cosmic microwave background radiation, and their possible relationship to the observed large-scale distribution of superclusters and voids that emerged as the Universe evolved.}

Question 8.3 In the case of Hubble's law, the Glossary notes that 'the greater a galaxy's redshift, the greater the distance', but the text is more explicit, stating that it is a proportional relationship (i.e. doubling one quantity implies a doubling of the other). The Glossary mentions the alternative formulation of Hubble's law in terms of distance and recession speed, but does not emphasise that this relates to the *current* values of those quantities, not the observed values. This distinction is unimportant for relatively nearby galaxies but, for very distant ones (that we see as they were long ago), it is difficult to determine either their distance or their speed of recession. The text includes the implications of Hubble's law; these could have been mentioned in the Glossary, but they were deliberately not included rather than it being an oversight.

In the case of Hubble's constant, the Glossary definition mentions the version of Hubble's law that involves recession speed, but not the version that involves the directly observable redshift. Also, there is no mention of the known uncertainty (about 10%), there is just a mention of the imprecise term 'about'. However, apart from this, all the main points seem to be included.

Question 8.4 The key points are: 'elastic space' is sanctioned by general relativity; it allows space to be described as curved or expanding; galaxies can be regarded as expanding with space rather than travelling through space; the wavelength of radiation can be stretched out as it travels through space (explaining Hubble's law); the expansion is a large-scale effect that is easily resisted by 'local' effects, e.g. the binding of planets, stars and individual galaxies. Of course, for the purposes of this question, which is largely directed towards writing skills, you are expected to include these points in a concise summary, not just a list. However, using the word 'concise' indicates that it should not be much longer than our list above.

Question 8.5 There is no 'right' answer to this question but you might have raised some of the following points. The skills box might have included a bulleted list of points to watch for. Hubble's law might have been presented as an equation, either in words or in symbols (that would need to be defined in the text). Hubble's law might also have been presented in the form of a properly explained graph. The brief outline of cosmic history could have been included in a table. The list of ingredients of the Universe (dark energy, matter of all kinds and radiation) might have been shown in the form of a 'pie chart' or another visual representation.

Question 9.1 1.4 million km is 1.4×10^6 km, so the ratio is $1.4 \times 10^6 \div 500$, i.e. 2800 or, more properly, 2.8×10^3. {See Chapters 2 and 3.}

Question 9.2 Figure 9.2 (overleaf) shows that, when Venus and Earth are on the same side of the Sun, only a small part of the illuminated surface of Venus is visible whereas, when they are on opposite sides,

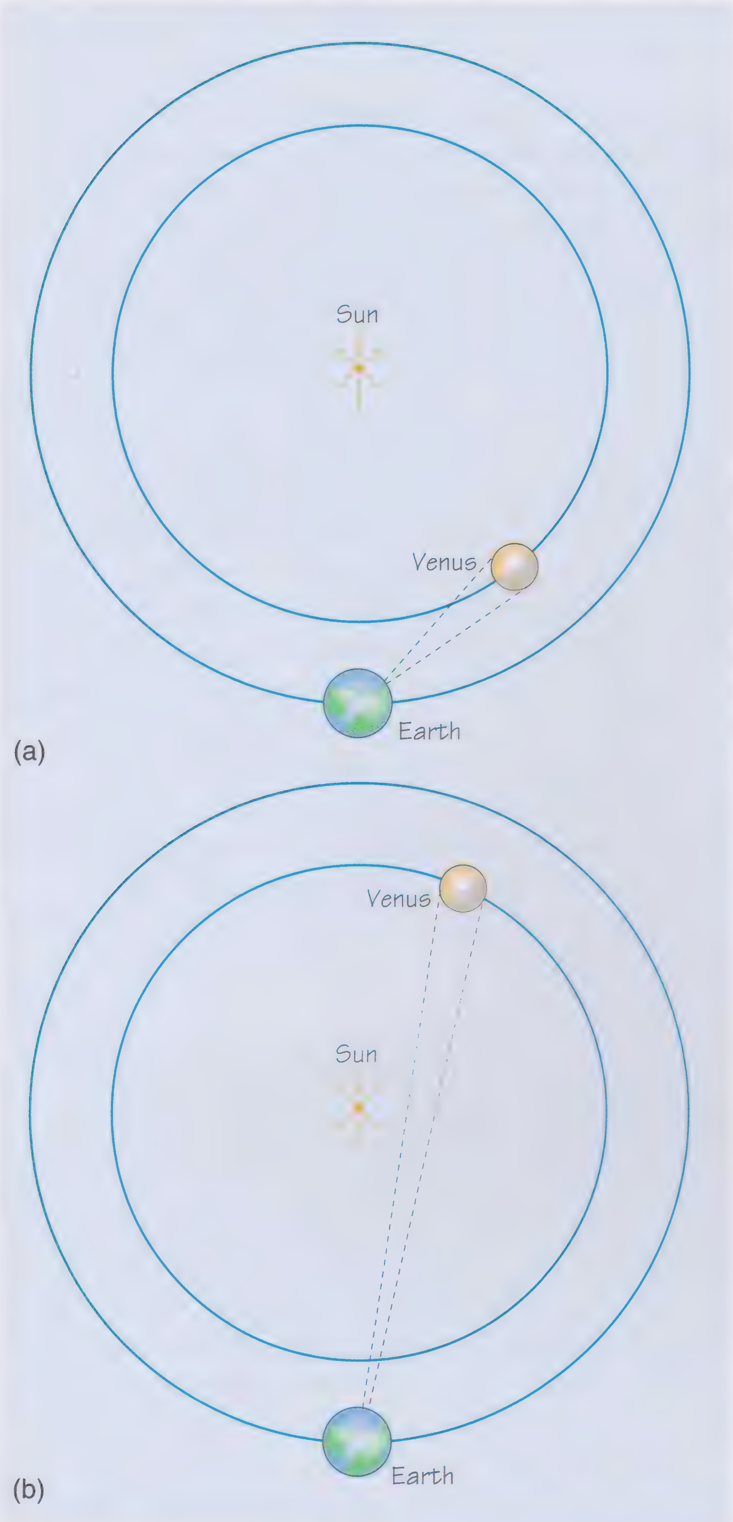


Figure 9.2 The changing appearance of Venus: (a) crescent phase, large angular size; (b) full phase, small angular size.

Venus appears 'full'. The angular size of Venus, as measured from Earth, is largest when it is close to Earth and smallest when it is furthest away, so the 'crescent' phases correspond to a large angular size and the 'full' phase is seen when the angular size is smallest. {See Chapters 2, 3 and 4.}

Question 9.3 Observed from Earth, Venus always lies in a similar direction to the Sun, so always appears close to the Sun in the sky. To appear in the midnight sky, Venus would need to lie in the opposite direction to the Sun, which never happens (see Figure 9.2). As Venus always appears close to the Sun, it is seen either in the western sky shortly after sunset or in the eastern sky shortly before sunrise. {See Chapters 3 and 4.}

Question 9.4 Liquid water is thought to be one of the essential requirements for the formation and evolution of living organisms. Planets containing a large proportion of icy material would form only at quite large distances from their parent stars, where temperatures are low enough to allow icy materials to form solid grains. If temperatures are so low, the planet will probably be too cold for water to be present in liquid form and hence unable to sustain living organisms. {See Chapters 3 and 6.}

Question 9.5 Molecular clouds in the ISM must be colliding, fragmenting and collapsing under their own gravity to form protostars and, eventually, stars. This gives rise to strong infrared radiation because the fragments heat up as they collapse and hence emit the infrared radiation characteristic of warm objects. Also, radiation (mainly visible and ultraviolet) from newly formed stars will heat the surrounding gas and dust so that it, too, emits in the infrared. {See Chapters 4 and 5.}

Question 9.6 If galaxies and quasars emit a lot of ultraviolet radiation, the effect of the redshift will bring this radiation into the visible part of the spectrum. If the light received contains more blue than red, the galaxy or quasar will appear bluish. {See Chapters 4 and 7.}

Question 9.7 You would need to explain that constellations are just apparent groupings of stars that appear in a similar direction when viewed from Earth but are not necessarily close to one another. When astronomers say that something is 'in' a constellation they mean it is seen in that part of the sky, which does not necessarily mean it is physically close to any of the stars. (You might go on to reassure your friend that what he or she remembers being told about nearby stars and distant galaxies is quite right.)
{See Chapters 4 and 7.}

Question 9.8 The brightness will peak at a longer wavelength. Over time, it will move from the microwave to the radio part of the spectrum. This is because the radiation depends on the temperature at which it is emitted, and a cooler object – a cooler Universe – will produce radiation at longer wavelengths. Another way to think of this is to visualise the wavelength of the radiation that pervades the Universe being 'stretched' as space itself expands. {See Chapters 4 and 8.}

Question 9.9 Given that Hubble's constant is 22 kilometres per second per million light years, a recession speed of 1320 kilometres per second for the brighter galaxy corresponds to a distance of $(1320 \div 22)$ million light years, i.e. 60 million light years. {See Chapter 8.}

Comparing the angular sizes indicates that the fainter one lies at about four times the distance (its angular size is one-quarter that of the brighter galaxy). {See Chapters 2 and 7.}

If this were the case, it would be expected to appear about one-sixteenth as bright – so 'a little less than one-fifteenth as bright' is what we would expect. Its distance would therefore be 4×60 million light years, i.e. 240 million light years. {See Chapter 4.}

One light year is 9.46×10^{12} km, so 240 million light years is $240 \times 10^{6} \times 9.46 \times 10^{12}$ km, i.e. 2.27×10^{21} km (near enough 2.3×10^{21} km). {See Chapter 4.}

Comments on activities

Activities 2.1 and 2.2 We have no further comments to add.

Activity 2.3 Figure 2.9 shows our summary description of the Sun based on Chapter 2. Yours may be presented in a different way but should include similar information.

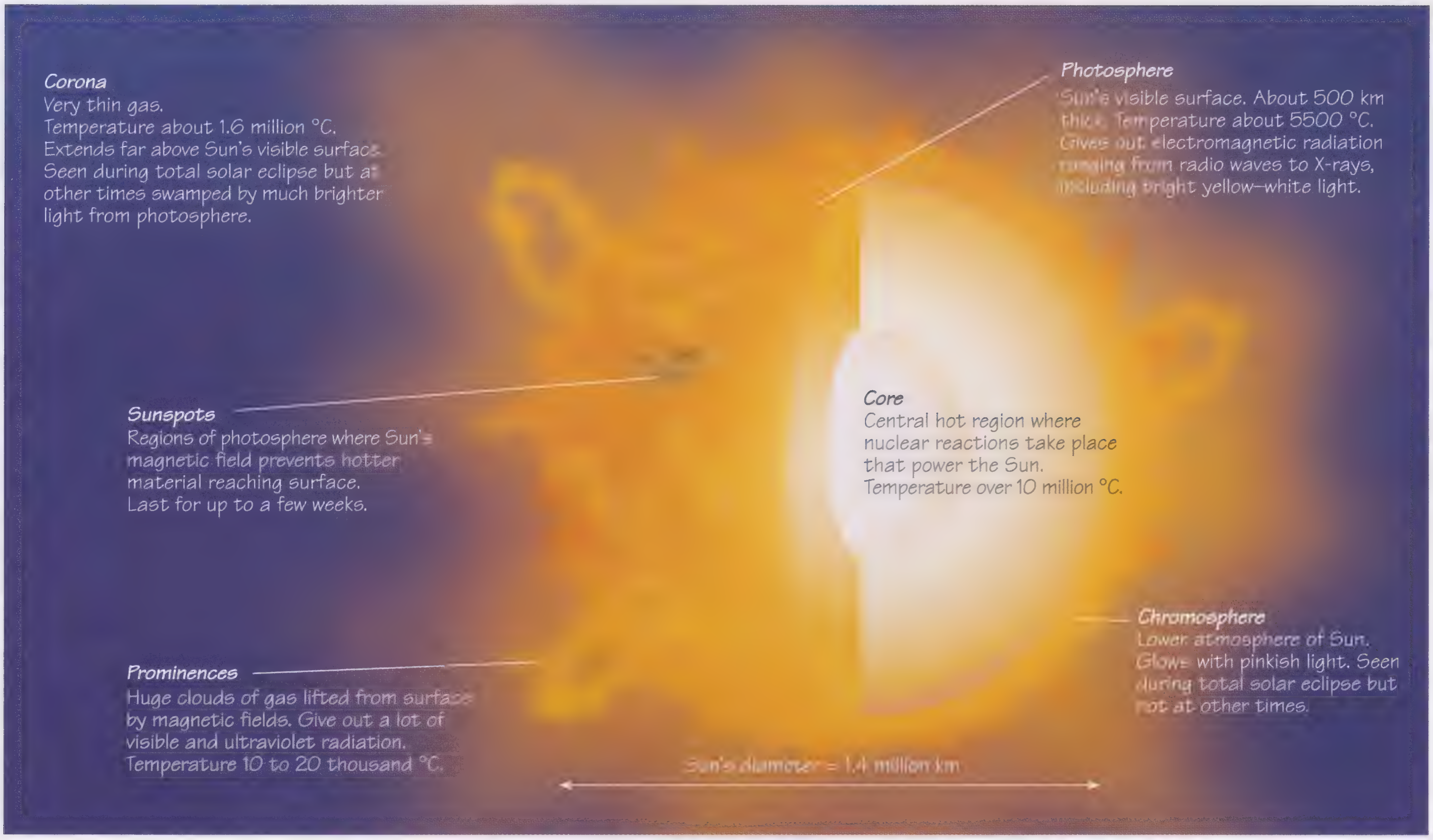


Figure 2.9 A possible drawing for Activity 2.3.

Activity 2.4 Here are some typical results from this activity:

- diameter of coin = 1.7 cm (UK 5 pence coin)
- distance of coin = 182 cm
- distance ÷ diameter = 107.058 82 on a calculator (near enough 107).

So, for something whose angular size is that of the Moon (half a degree):

- distance = 107 × diameter
- diameter of Moon = 3476 km.

Therefore, distance of Moon = 107 × 3476 km, i.e. distance of Moon = 371 932 km (near enough 372 000 km).

To eclipse the Moon, the distance of the coin needs to be roughly one hundred times its diameter. If you tried using a coin larger than 2 cm diameter, it would need to be more than 2 m from your eye and would not fit on a 2 m rod.

Our result is quite close to the accurately measured value of 384 500 km; yours may be closer, or not quite so close. Provided you got a value of a few hundred thousand kilometres, that is reasonable. If your value was very different, check back through your calculations to see whether you have made a mistake, and look again at your measurements.

Activity 3.1 In the first part, you might have found that the table-tennis ball did not move exactly in a straight line. This might happen if the surface was not level, or if either the ball or the table were not completely smooth. If you inadvertently spun the ball, and there was some friction between the ball and the table, that would also drive it into a curved path.

In the second part, the cork flies off in the direction it was heading, and falls in a curved path towards Earth. It is being pulled downward by gravity. If there was no gravity it would move horizontally in a straight line.

Activity 3.2 Almost any aspect of visual appearance could be used to classify the planets and give some insight into their nature. For example, the size of a planet might well be related to the materials it is made from and the way in which it formed (indeed, this seems to be the case). However, some aspects of visual appearance are less helpful. For instance, the colours of the planets also depend on the materials that make up their surfaces, so we might expect planets of similar colour to be made of similar materials. In practice, though, colour can be misleading: Mars and Jupiter both have parts that appear red, but on Mars this is caused by red-coloured rocks while Jupiter's red regions (e.g. the red spot) are caused by gases in its atmosphere.

Size seems to be a useful basis of classification, with a group of small planets (Mercury, Venus, Earth, Mars and Pluto), and a group of large planets (Jupiter, Saturn, Uranus and Neptune, possibly subdivided into Jupiter and Saturn in one subclass, and Uranus and Neptune in the other).

One indication of a useful characteristic is that it ties in with others. If two different ways of classifying planets lead to the same planets being grouped together, this suggests there may really be some underlying similarities. For example, the fact that all the planets with rings also have many natural satellites and are very much larger than Earth indicates that their similarities are not merely superficial.

Activity 3.3 You should have found one, and usually several, examples of each process on more than one different body. Note that at least one of these processes (cratering) occurs on asteroids and comets, which do not really qualify as a planet or a satellite.

Activity 4.1 The answers below are for an observer or a planisphere at latitude 55° North.

1 The times (to the nearest 10 minutes) at which Betelgeuse is on the eastern horizon (rising) are:

1 January	16:20	1 April	10:20
1 July	4:25	1 October	22:30

{If using a planisphere for northern mid-latitudes, you might have obtained times up to 101minutes earlier or later, depending on how you set the star on the horizon. You may obtain different times from the planetarium software if it is set to your true location.}

2 Betelgeuse rises until it is at its highest in the sky (in the southerly direction) at the following approximate times.

1 January	23:15	1 April	17:15
1 July	11:20	1 October	5:25

Betelgeuse continues towards the western horizon and crosses it (sets) at approximately:

1 January	6:10	1 April	0:20
1 July	18:20	1 October	12:20

3 The interval between the rising and setting of Betelgeuse is about 14 hours on all four dates. However, on 1 January the night is long, and Betelgeuse rises near to sunset and sets an hour or so before sunrise. It is therefore actually visible for the longest on 1 January out of the four dates.

{You might have obtained a slight difference between rising and setting from one date to another using the planisphere, but this is due to imprecision in locating a star on the horizon. The interval between rising and setting of any star is the same throughout the year, as you will have found using the planetarium software.}

4 The Plough does not rise or set – it is in the sky all the time in the Northern Hemisphere. {This depends on latitude. For example, if you were at the Equator, the Plough *would* rise and set. Deep into the Southern Hemisphere it is always below the horizon, permanently hidden from view by the Earth.}

Activity 4.2 Your results for this activity will depend on where and when you carried it out!
We hope that you will continue looking at the stars whenever you get a chance, and become familiar with their patterns and colours – particularly when you are somewhere that has clear, dark skies.

If you observed several times during one night, you will have seen how the stars appear to move across the sky. Like the Sun and the Moon, stars rise in the east and set in the west – except for those that remain high in the sky throughout the night. These sweep around in anticlockwise circles centred on a point above the North Pole (which coincides closely with the position of the 'north star', Polaris). The time for one complete circle about Polaris is slightly less than 24 hours (actually 23 hours 56 minutes). Any given star rises about 4 minutes earlier each day. This is hardly noticeable from one day to the next, but if you extend your observations over a week or so, you will become aware that stars do not return to exactly the same positions at the same time, but each night appear slightly further on in their anticlockwise motion.

If you extended your observations over a period of more than a few days, you might have seen that planets change their position relative to the stars.

Activity 4.3 See the text in Chapter 4 that follows this activity.

Activity 5.1 Stars will not form in every part of the interstellar medium. They are only likely to form in the coolest and most dense regions, such as molecular clouds. In some regions, the ISM is being dissipated by the presence of newly formed, hot stars. Some interstellar clouds are the remnants of the death of stars.

Infrared (and microwave) wavelengths of electromagnetic radiation are best for observing protostars because they can penetrate through dust that is opaque at optical wavelengths.

Younger, open clusters are more likely to have associated nebulae left over from their formation because they have not had time to completely dissipate due to the intense starlight from the brightest cluster stars.

Globular clusters have more regular shapes (spherical versus often irregular) and more stars (in the order of a million versus a few hundred), which are more densely packed and much older than open clusters. They are located in a spherical 'cloud' about the galaxy, whereas open clusters are predominantly found in or near star-forming regions (i.e. the disc of the Milky Way).

Activity 5.2 After doing this activity, you should be able to explain why generally just one pulse is observed for each revolution of a pulsar, despite the beam emerging in two directions; two pulses would be observed only if the beam emerged at right angles to the pulsar's rotation axis. This activity also illustrates how pulsars might remain unobserved – they can only be seen if their radiation happens to be beamed in our direction.

Activity 5.3 Your sketch should consist of the main cycle shown in Figure 5.11 plus a branch to stellar remnants, with appropriate labels and at least one example of an image for each stage. {Note that the images generally illustrate the stages – for example, dense clouds – rather than processes, such as stellar evolution.}

Activity 6.1 {Our answer consists of Table 6.1 (opposite) followed by the paragraph of overall considerations. You probably organised your answer differently. The 'Comment(s)' column in the table is not expected as part of your answer.}

The most relevant data (from Section 6.2.2) are the mean surface temperature and mean surface pressure, because these determine whether water can exist as a liquid. The information about atmospheric composition is not very relevant because it does not list the main components.

Activity 6.2 Impact craters accumulate on a surface and are subsequently obliterated by any resurfacing. Therefore, if a planetary body has a heavily cratered terrain and a lightly cratered terrain, the heavily cratered terrain will be older.

{To turn this into absolute ages, we use the variously cratered terrains on the Moon, for which we have absolute ages. These have been obtained by radiometric dating of rock samples from these terrains – the details need not concern us. There are difficulties in applying lunar data to Mars and, consequently, the absolute ages of the Martian terrains are poorly known.}

One way of demonstrating the principle is to prepare a smooth surface of fine sand and throw water droplets at it every few seconds. The number of pits formed by the droplets grows with every throw. The pits can be removed by resurfacing the sand.

Table 6.1 For Activity 6.1.

Planet	Potential habitat? Reason(s)	Comment(s)
Mercury	No. Atmospheric pressure is too low.	The mean surface temperature is also too low, although this is a little misleading. Mercury rotates very slowly – it has a long day – and so one side is very hot and the other is very cold.
Venus	No. Mean surface temperature is much too high.	Temperatures vary little across the Venusian surface, so there are no cool niches.
Mars	Unlikely. Mean surface temperature is too low, and atmospheric pressure is marginal.	In fact, at certain times, the temperature can exceed 0 °C, so atmospheric pressure is the problem.
Jupiter	Insufficient information given. The pressure and temperature increase with depth into the atmosphere, but it is not possible to say whether there is a level where liquid water could exist.	In fact, there is an atmospheric level where the temperatures and pressures would allow liquid water, and water is present in the atmosphere. Deeper down it is too hot. However, life is unlikely to emerge at any level in this atmosphere.
Saturn	As for Jupiter	As for Jupiter
Uranus	As for Jupiter	As for Jupiter
Neptune	As for Jupiter	As for Jupiter
Pluto	No. Too cold.	At its huge distance from the Sun, no part of Pluto's surface reaches anywhere near 0 °C. Also, the atmospheric pressure is well below 6.1 millibars.

The satellites of the planets should also be considered. The Moon is ruled out because of its very low surface pressure and extremes of temperature but, among the satellites of the giant planets, there is one promising candidate, as you will see.

{There are many other possible demonstrations. One advantage of using water is that, as in the real case, none of each projectile (water drop) remains. In the real case, they vaporise on impact; in the demonstration, they slowly evaporate.}

Activity 6.3 We have no further comments on this activity.

Activity 7.1 Table 7.1 summarises the distinguishing characteristics of elliptical, lenticular, spiral and irregular galaxies.

Table 7.1 Characteristics used to classify galaxies.

Galaxy class	Distinguishing characteristics
Elliptical	Elliptical outline; smooth distribution of brightness, brightest in centre Little or no active star formation
Lenticular	Lens-shaped Disc of stars embedded in a stellar halo No spiral arms May have a central bar
Spiral	Disc of stars embedded in a stellar halo Spiral arms and central bulge Contains clear regions of active star formation May have a central bar
Irregular	No overall regular shape; uneven distribution of brightness Contains regions of active star formation

Activity 8.1 Suppose your unstretched band had one dot (A) 2 cm from the 'Milky Way' and another (B) at a distance of 4 cm. After stretching the band to 1.5 times its original length, the first dot would be 3 cm from the 'Milky Way' and the second 6 cm. Viewed from the 'Milky Way', dot A would have receded through 1 cm and, in the same time interval, B would have receded through 2 cm: observed from the 'Milky Way', B would have moved twice as far and twice as fast as A. This illustrates a general point: the more distant galaxies recede more rapidly than those closer to the observer. This does not depend on the 'Milky Way' being in any particular location: it could be near the middle of the row of dots or at the end.

Activity 8.2 A recession speed of 1000 kilometres per second implies a distance of (1000 ÷ 22) million light years, i.e. 45 million light years.

This is a fairly large distance, bigger than the diameter of the Local Group, but not as large as the diameter of the Local Supercluster. It would be quite reasonable to apply Hubble's law on this sort of size scale, but it would also be realistic to expect that a galaxy observed at this distance might still have its movements 'contaminated' by clustering effects. Basically, the gravitational attraction of nearby superclusters might cause it to deviate from the 'Hubble flow' associated with general cosmic expansion. So, as is often the case in astronomy, the answer is proceed with caution.

If we apply Hubble's law without thinking much about its meaning, a recession speed of 100 kilometres per second corresponds to a distance of less than 5 million light years. This would put the galaxy concerned only a little beyond the boundary of the Local Group and should make us very concerned about the reliability of Hubble's law.

However, 10 000 kilometres per second is an entirely different proposition. This implies a very great distance, where the cosmic recession speed caused by universal expansion (the Hubble flow again) is likely to be significantly larger than any 'local' effect caused by clustering. In this case, Hubble's law can be applied with some confidence.

Acknowledgements

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Glossary

Cross-references are in *italic*.

absorption spectrum A pattern of narrow dark lines crossing a generally bright spectral background, indicating narrow ranges of wavelengths that have been absorbed in some way.

active galaxy A *galaxy* that produces far more radiation than can be accounted for by the stars and *interstellar medium* that it contains. The brightness of active galaxies often varies significantly on time-scales of weeks or months.

active region A localised volume of the *Sun's* outer layers in which enhanced magnetic fields give rise to transient phenomena such as *sunspot* groups (in the *photosphere*), plage (in the *chromosphere*) and coronal condensations (in the *corona*). Such regions are also associated with *flares*.

angular size The angle between two lines drawn from an observer's eye to opposite sides of the object being observed.

asteroid A small rocky body found mainly between Mars and Jupiter.

astronomy The study of the celestial bodies and the regions of space between them.

atom The smallest building block of a molecule.

big bang The event that marks the beginning of cosmic expansion.

binary star Two *stars* in orbit around each other.

black hole The highly condensed remains of a *star*, whose gravity is so strong that not even light can escape.

blueshift A quantity used to describe a decrease in the wavelength of radiation received from a source, usually recorded as a negative *redshift*.

bulge A structural component of the *Milky Way*, consisting of a thick, dense concentration of *stars* around the centre of the disc. Bulges are a common feature of spiral and lenticular *galaxies*. In the case of the Milky Way (and many other galaxies), the bulge is elongated to form a bar.

celestial coordinates A system of coordinates – *declination* and *right ascension* – used to denote positions on the *celestial sphere*, analogous to the geographic coordinates of latitude and longitude, used to determine positions on the Earth's surface.

celestial sphere An imaginary sphere surrounding the Earth on which the *stars* appear to be fixed.

centripetal force A force directed towards the centre of any circular motion. Such a force is essential for maintaining motion in a curved path.

chemical compound A substance in which the smallest unit consists of more than one type of *atom*.

chemical element A substance containing only a single type of *atom*.

chromosphere The lower part of the *Sun's* atmosphere.

cluster A gathering of *galaxies* in a region of space typically 12 to 15 million *light years* across. Some clusters are rich, but sparse clusters, with fewer than 50 members, are also known as 'groups'.

comet A small icy body left over from the formation of the *Solar System* that partially evaporates if it approaches the *Sun*, generating long tails.

constellation Any of the 88 designated regions that jointly cover the whole celestial sphere.

continuous spectrum A smooth and unbroken *spectrum*, often presented as a band of rainbow-like colours.

convection zone A layer of the *Sun's* interior, immediately below the *photosphere*, in which energy is transported towards the surface by the process of convection (heated material rises upwards while cooler material descends from above to replace it).

core (of a star) The central, very hot region of a *star* (such as the *Sun*) where *nuclear reactions* can happen.

corona The upper part of the *Sun's* atmosphere. It is very hot, very tenuous and very extensive.

cosmic microwave background radiation The highly uniform microwave radiation that comes with very nearly equal intensity from all directions in space. It is believed to be the expanded, cooled and

redshifted remnant of the radiation emitted at a temperature of about 3000° C, when the cooling Universe first became transparent.

cosmological constant A quantity introduced by Albert Einstein in his general theory of relativity that effectively gives rise to a long-range repulsion, which could account for the observed acceleration of cosmic expansion. The effect of Einstein's cosmological constant can be reproduced by an appropriate distribution of *dark energy*.

dark energy Energy of currently unknown origin that has become the dominant influence on cosmic expansion and is currently causing that expansion to accelerate. Dark energy is thought to account for about 70% of all the energy in the Universe. It is not thought to be associated with *dark matter*, but may be related to Einstein's *cosmological constant*.

dark halo A structural component of the *Milky Way*, consisting of an extensive (spherical?) distribution of *dark matter*, within which all the other components are embedded. The dark halo is the largest and most massive component of the Milky Way. Similar dark haloes are believed to be present in other *galaxies*.

dark matter A currently mysterious form of matter that neither absorbs nor emits any detectable radiation, but can be detected and studied through its influence on directly observable ('bright') matter.

declination A celestial coordinate measured perpendicular to the celestial equator; analogous to geographical latitude measured perpendicular to the Earth's equator.

dense cloud See *molecular cloud*.

disc A structural component of the *Milky Way*, consisting of a disc approximately 100 000 light years in diameter and a few thousand light years thick that contains approximately 10^{11} stars, together with gas and dust. Similar discs are present in other spiral and lenticular *galaxies*.

Doppler effect The effect that causes the observed *wavelength* of radiation to differ from its emitted wavelength, as a result of the relative motion of the source and the observer.

electromagnetic radiation A type of radiation that includes visible light and can travel through empty space at the speed of light. All forms of electromagnetic radiation consist of wave-like patterns of electric and magnetic disturbances.

electromagnetic spectrum The full family of closely related types of *electromagnetic radiation*, usually arranged in order of increasing or decreasing wavelength. The traditional divisions of the electromagnetic spectrum are (in order of decreasing wavelength): radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

ellipse A closed curve with the shape of a flattened circle. To a good approximation, *planets* move in elliptical orbits around the *Sun*.

emission spectrum A pattern of narrow bright lines crossing a generally dark spectral background, indicating narrow ranges of wavelengths that have been emitted in some way.

error (in a quantity or a measurement) The difference between the quoted value and its true value. The error is not normally known – an estimate of its possible value is the *uncertainty* in a measurement.

exoplanet A *planet* orbiting a *star* other than the *Sun*.

flare A highly energetic form of solar activity, typically lasting a few hours, caused by the sudden release of magnetic energy in the *corona*.

galaxy A vast assembly of *dark matter* and luminous matter, typically tens of thousands of *light years* in diameter and containing billions of *stars*, held together by the mutual gravitational attraction of its constituents.

general relativity A theory developed by Albert Einstein that provides a mathematical description of space and time and relates the properties of space and time to those of the matter and radiation it contains. General relativity uses the idea of space–time distortion (curvature or expansion) and constitutes Einstein's theory of gravity.

giant planet A *planet* considerably larger than the Earth, composed largely of hydrogen and helium (cf. *terrestrial planet*).

globular cluster A cluster of 10^5 to 10^6 old *stars*, tightly bound by gravity into a spherical region of space, typically about 100 *light years* in diameter. They are found in a spherical distribution about the centre of our *galaxy* and in other galaxies.

granules Small, short-lived, bright patches of the *Sun's photosphere* that correspond to the tops of rising columns of hot material in the *convection zone* below.

group A gathering of *galaxies* with fewer than 50 members, believed to be bound together by gravity.

Hubble classification scheme A scheme for the classification of *galaxies* according to their observed shape, based on the classes elliptical, lenticular (i.e. lens-shaped), spiral (barred or normal) and irregular.

Hubble's constant The constant (usually denoted H_0) that relates the speed of recession of a sufficiently remote *galaxy* to its distance at the present time. H_0 describes the present rate of (large-scale) expansion of the Universe, and is thought to have a value of about 22 kilometres per second per million light years.

Hubble's law The observation that, for distant galaxies, the greater a galaxy's distance, the greater the *redshift* of the radiation received from that *galaxy*. (This is sometimes expressed by saying the galaxy's speed of recession is proportional to its distance.)

icy materials Materials that melt or evaporate easily, so are normally liquids or gases on the Earth's surface (cf. *rocky materials*).

interstellar medium (ISM) The very thin gas and tiny specks of dust that lie between the *stars*.

light year The distance that *electromagnetic radiation* travels through space in one year, i.e. 9.46×10^{12} km.

Local Group The sparse cluster containing about 40 known *galaxies* that includes the *Milky Way* and all the other galaxies within about three or four million *light years*.

Local Supercluster The *supercluster* centred on the rich Virgo cluster of *galaxies* that includes the *Local Group* as an outlying constituent.

lunar month The average time between two successive new Moons, i.e. 29.53 days.

lunar phase A particular shape of the illuminated surface of the Moon, as seen by an observer, e.g. full Moon, half-moon.

magnetic field The quantity associated with a magnetic body, such as the Earth or the *Sun*, that determines the magnetic force that body will exert on other specified bodies (such as a magnet or moving charged particles) in its vicinity. A magnetic field has both a strength and a direction at any point in the region that it occupies.

main sequence star A *star* powered by the *nuclear reactions* of hydrogen within its core.

meteor A small rocky object originating outside the Earth that enters the Earth's atmosphere and can be seen travelling through it.

meteorite Any surviving fragment of a *meteor* that enters the Earth's atmosphere, where it partially burns up before landing.

Milky Way The large, barred, spiral galaxy in which the *Sun* is located. Also, the name applied to the band of milky light seen in the night sky attributable to the surrounding parts of the disc of *stars* that contains the Sun.

molecule A group of two or more *atoms*, each atom being the simplest form of a *chemical element*.

molecular cloud A cold, relatively dense region of the *interstellar medium*. Also known as a *dense cloud*.

nebula A loose term, literally meaning 'cloud', applied to any interstellar object that appears extended or 'fuzzy' (in contrast to *stars*, which look point-like).

neutron star A stellar remnant of mass rather more than the *Sun*, with a diameter of only about 20 km, formed from the collapsed *core* of a *supergiant* star after a *supernova*.

nuclear reactions Processes in which the constituents of atomic nuclei are changed or rearranged. Such reactions can release substantial amounts of energy. They provide the ultimate power source for nuclear weapons, and for the *Sun* and *stars*.

Oort cloud A spherical cloud of icy bodies surrounding the *Solar System* and extending up to one-third of the way to the nearest *star*. It is named after the Dutch astronomer Jan Hendrik Oort (1900–1992) who first postulated its presence.

open cluster A cluster of a few hundred *stars* that formed at the same time, loosely bound together in an open structure. They are found predominantly in regions of our *galaxy* where stars form.

parsec A unit of distance used in astronomy: 1 parsec (pc) = 3.09×10^{13} km = 3.26 light years.

peculiar galaxy A *galaxy* that can be assigned to a Hubble class but has a peculiarity that distinguishes it from typical members of that class, possibly as a result of merging or colliding with another galaxy.

photosphere The bright visible surface of the *Sun* (or any similar *star*).

photosynthesis A process in certain types of organism in which water and carbon dioxide are used in the first stage of the synthesis of complex carbon compounds, usually releasing oxygen as a by-product.

planet One of the nine major bodies orbiting the *Sun*, or a similar body orbiting another *star*.

planetary nebula The glowing, ejected outer layers of a *star*.

planisphere A device for displaying which *stars* are above the horizon at any particular time on any particular date.

prograde A term used to describe orbital or rotational motion. In the context of the Solar System, it means motion that is anticlockwise when viewed from above the North Pole of the Earth. See also *retrograde*.

prominence A spurt of hot solar material seen extending outwards from the edge of the *Sun*.

protostar A collapsing fragment of a *molecular cloud* that eventually becomes a *star*.

pulsar The rapidly spinning, dense central part of a *star* that remains after a *supernova*; detected by its regular radio pulses.

quasar A type of highly luminous, active *galaxy* with a *star*-like appearance, that was more common when the Universe was younger.

radiation That which is radiated from a source and travels through space. Often used as an abbreviation for *electromagnetic radiation*.

radiative zone A layer of the *Sun's* interior, between the core and the *convection zone*, in which energy is transported towards the surface by the repeated emission and absorption of *electromagnetic radiation*.

red giant A large, cool *star* that is going through subsidiary stages of *nuclear reactions*, having exhausted the hydrogen fuel supply in its core.

redshift A quantity used to describe an increase in the wavelength of radiation received from a source. Causes of redshift include recessional motion (see *Doppler effect*), and the passage of *radiation* through expanding space.

retrograde A term used to describe orbital or rotational motion in a direction which is opposite to that regarded as normal or conventional. In the context of the Solar System, it means motion that is clockwise when viewed from above the North Pole of the Earth. See also *prograde*.

right ascension A celestial coordinate measured along the celestial equator (in units of hours, minutes and seconds), analogous to geographical longitude measured along the Earth's equator.

rocky materials Materials that require high temperatures in order to melt (cf. *icy materials*).

rubble pile A body (typically an *asteroid*) with a structure composed of a loosely bound collection of particles held together only by gravity.

satellite An object in orbit around a larger one, e.g. a 'moon', or an artificial space probe orbiting a *planet*.

scientific notation The convention of writing any number as a small number (between 1 and 10) multiplied by a power of ten, e.g. 780 000 is written 7.8×10^5 and 0.000 34 is written as 3.4×10^{-4}.

solar eclipse The partial or complete blocking of the *Sun's photosphere* by the Moon.

solar nebula The hypothetical cloud of gas and dust within which the *Sun* and other constituents of the *Solar System* formed.

solar neutrinos Uncharged particles, emitted by the *nuclear reactions* taking place in the *core* of the *Sun*, that can be detected on Earth and used to study the condition of the Sun's interior.

solar oscillations Quaking motions involving the whole *Sun* that can be observed on its surface and used to investigate its interior.

Solar System Our *Sun* and all the bodies associated with it (*planets*, their *satellites*, *comets* and *asteroids*).

spectral line A narrow line in the spectrum of *electromagnetic radiation* from a *star* or other object. The *wavelengths* of spectral lines depend on which substances are present.

spectrum A range or distribution, usually referring to types of *electromagnetic radiation*, especially when arranged in order of increasing or decreasing *wavelength* and possibly accompanied by information about intensity or brightness.

star A large, near-spherical object that emits *electromagnetic radiation* through self-sustaining *nuclear reactions* in its interior.

stellar halo A structural component of the *Milky Way*, consisting of many faint *stars*, within which the disc and bulge components are embedded. The stellar halo also houses the Milky Way's retinue of *globular clusters*. Similar stellar haloes are present in other *galaxies*.

Sun The *star* at the centre of the *Solar System*.

sunspot A small, relatively cool region of the Sun's *photosphere* that appears as a dark spot on images of the visible *Sun*.

supercluster A gathering of clusters of *galaxies*, typically containing one or two rich *clusters*, possibly somewhat flattened or drawn out into filaments, and separated from other superclusters by one or more *voids*.

supergiant A *star*, several times more massive than the *Sun*, after it has exhausted the hydrogen nuclear fuel supply in its core.

supernova A dramatic stellar explosion, produced when a *star* several times the mass of the *Sun* has exhausted its nuclear fuel.

supernova remnant The extended and expanding remains of a *star* following a *supernova*.

synchronous rotation The rotation of a *satellite* on its own axis that exactly matches its orbital period about a *planet*.

terrestrial planet A *planet* similar in size to the Earth, composed of *rocky material* (cf. *giant planet*).

tidal heating Heating resulting from a variation in the tidal deformation of an object (tidal deformation being the result of different gravitational forces exerted by a second object on different parts of the object in question).

total eclipse of the Sun A natural phenomenon that occurs when the Moon passes between the Earth and the *Sun*, and completely blocks the view of the Sun's bright *photosphere* as seen from certain places on Earth.

trans-Neptunian objects Many icy bodies in the outer *Solar System*, believed to be left-over material that did not form *planets*.

uncertainty (in a quantity or a measurement) An estimate of the difference (*error*) between a quoted value or measurement and its true value.

void A large region of space, comparable in size with a *supercluster*, that is almost devoid of luminous matter.

wavelength The distance between successive peaks of a wave.

white dwarf A small hot *star*, left behind when a *red giant* throws off its outer layers as a *planetary nebula*.

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